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FOREWORD

IT IS the purpose of this journal to provide an interdisciplinary medium through which Advanced Energy Conversion can be treated as a coherent subject. This first issue illustrates one function of the journal, the publication of the proceedings of outstanding scientific symposia devoted to energy conversion. Regular issues will include high caliber scientific papers on all the electrical conversion processes, both direct and dynamic; and on the related subjects of energy sources, energy storage and control processes. A Technology Section will present new systems concepts, advances in engineering practice, fabrication techniques and materials developments.

The scope of the journal is thus very broad and embraces contributions from many scientific disciplines. It is hoped that in addition to serving as a focal point for progress in these diverse fields with the common goal of improved power sources, that scientists in each of the disciplines will benefit from recognizing the relationships between the concepts expressed in the nomenclature of his field with similar problems and concepts expressed by the different models and different nomenclature of other fields. If as time goes on there is recognition of common concepts in different cloaks, and if there is a cross fertilization of ideas, the journal will have accomplished its mission.

SESSION I

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PHOTOELECTRIC PROCESSES

PAUL RAPPAPORT*

1. INTRODUCTION

IN THIS category are considered two energy conversion processes. One is that using the photovoltaic effect (solar cells), and the other is the photoelectric effect where electrons are emitted from a surface into a vacuum where they are collected by a transparent electrode. Both of these conversion techniques are quantum devices where individual photons from the sun (or other light source or radioactive material) cause quantum transitions in a metal or semiconductor to release charge carriers for electrical current flow in an external circuit. These are to be contrasted to the thermionic and thermoelectric devices which are heat engines. This discussion will be concerned chiefly with solar cells but a few remarks will also be made concerning true photoelectric devices.

2. SOLAR CELLS

(*a*) *Description*

Solar cells are commercially available in quantity with overall solar conversion efficiencies up to 14 per cent. At present they are made of single-crystal silicon. A *p–n* potential barrier (junction) is required for carrier separation and collection and is made by diffusing into the silicon a suitable impurity such as boron at a temperature near 1000°C. This barrier must be close to the surface where solar photons are absorbed. In practice a depth of about one micron is satisfactory for efficient energy conversion. One electrical connection is made to this thin diffused region and another to the undisturbed region to give a positive and negative terminal. Typically, each silicon solar cell (1 × 2 cm) yields about 1/2 volt and 50 mA when exposed to sunlight. Many cells must be connected in series for higher voltage or in parallel for higher current. Because of the location of the contacts on the top and bottom of each wafer the series connection is made by "shingling" cells together so that each series chain consists of cells overlapping one after another.

(*b*) *State of the art*

Silicon solar cells (approximate cost $600,000/kW coated and mounted) have powered several satellites satisfactorily. *Explorer 6*, *Tiros I*[1], and *Explorer 7* are among the satellites using large numbers of solar cells; the first two satellites operated successfully for three months, and the last one was still operating after more than one year. An early Vanguard satellite has been operating (at least the solar cells are still supplying power) after almost four years. These cells have the advantage over other power sources in that they do not require accurate attitude control (orientation), a collector or a radiator. They are basically a light-weight device. The silicon cell without support weighs about 20 lb/kW; with support, 180 lb/kW represents present day design for panel mounted cells. If the weight of the

* Radio Corporation of America, Princeton, New Jersey, U.S.A.

storage device is to be included, this number must be increased. Large-area thin-film cells, of course, offer the promise of extremely light weight. The table below shows the various photovoltaic materials and the best reported room-temperature efficiencies to date. This is for single-crystal material unless otherwise marked.

TABLE 1. EFFICIENCIES REPORTED FOR SOLAR CELLS [2]

Material	Energy gap (eV)	% Efficiency
Si	1·1	15
GaAs	1·35	10
Cds	2·4	8
		5*
CdTe	1·45	4
InP	1·25	3
Se	1·0	1*
GaP	2·35	1

* Polycrystalline film.

(*c*) *Theoretical limitations*

The theoretical overall efficiency of conversion for a solar spectrum is about 24 per cent when ideal conditions are assumed for the *p–n* junction characteristic. The semiconductor energy gap would have to be about 1·5–1·6 eV. For silicon the maximum theoretical efficiency is about 20 per cent. For a monoenergetic photon source this conversion efficiency could extend to 50 per cent.

The most important factor preventing the achievement of this theoretical limit is the internal loss of solar-generated carriers due to bulk recombination. The so-called minority-carrier diffusion-length of the processed semiconductor is too small. This diffusion length ideally should be of the order of the reciprocal of the absorption constant for the photons with energy near the band gap energy of the semiconductor. Thus diffusion lengths of 10^{-1} to 10^{-2} cm are required whereas in practice they are 10^{-4} to 10^{-2} cm.

(*d*) *Operation at higher than room temperature*

Where operation at higher temperatures is required, such as in conjunction with light-concentrating systems or for some satellite missions, the optimum photovoltaic material changes. In general an elevation in temperature results in reduced efficiency of solar cells. Usually, the higher the semiconductor band-gap the less is this reduction. Thus, the efficiency degradation with temperature of silicon (band-gap 1·1 eV) cells is approximately twice that of GaAs (band-gap 1·35 eV). For example, at 100°C a silicon cell's efficiency is only 50 per cent of the value at 0°C while a GaAs cell's efficiency is 80 per cent of its 0°C value. GaP (band gap 2·3 eV) is even better than GaAs in this respect, however CdS (band gap 2·4 eV) does not behave like a wide-gap semiconductor and has a temperature-dependence resembling that of silicon. This appears to be caused by a different photovoltaic mechanism in the CdS cell.

In connection with higher-temperature operation it should be pointed out that normal silicon cells have low emissivity coefficients (about 0·3) at long wavelengths so that they

have a tendency to heat up during operation thus lowering their efficiency. Naturally a wider-gap material would be better for such operation, however it has been found that coatings or coverings over the cells can increase their long wavelength emissivity to about 0·9, thus lowering their operating temperature. Typical cell coatings are glass, quartz, silicon monoxide or plastic coatings. In applying these coatings the "greenhouse" effect must be avoided or the cell temperature may be raised. This is simply accomplished by having the coatings in intimate contact with the cell surface.

(*e*) *Reliability*

In general, solar cells are quite reliable devices in that no moving parts are involved nor is there anything that is used up. Operation is at moderate temperatures so that diffusion or alloying effects are non-existent. Single-crystal semiconductors are quite brittle and apt to crack and contacts are prone to separation. This is especially true when the cell structures are subject to extreme variations in temperature, as when going through eclipses. These problems are under good control in silicon although as new materials are introduced the problems may occur again. Meteorite damage is an ever-present hazard that usually results in an open circuit. By judicious series–parallel connections, one can minimize the seriousness of such effects.

The major cause of solar cell degradation will probably be due to the effects of radiation such as the protons and electrons of the Van Allen Belts. For example, in the lower radiation belt Van Allan has estimated that there may exist a flux of about 4×10^4 protons/cm^2 per sec of average energy of about 50–100 MeV. Laboratory measurements indicate that a solar cell will degrade to about 75 per cent of its initial efficiency after receiving about 10^{11} protons/cm^2. This means that after 1000 hours of operation in the lower Van Allen Belt a solar cell will deliver about 75 per cent of its initial power. The dependence is such that for a degradation to 50 per cent initial power it takes an additional 2000 hours operation in the radiation belt. A similar situation exists for electrons. However for electrons it is possible to do an effective shielding job (for energies below 1 MeV) but with the high-energy protons this is impractical because the weight of the shield would be prohibitive. Since surface coatings of cells are required for proper heat balance some shielding against particle irradiation is provided. However, the additional problems of radiation effects in the coatings and adhesives must be considered. Cerium glass or quartz are (when compared to the silicon cell) radiation resistant and would be satisfactory for cell coatings.

Recent work has indicated the possibility of improving the radiation-resistance of solar cells by special construction or the use of new materials. For example, if a silicon cell is made so that the top surface layer is *n* type (it is *p* type in commercial cells) we have what has been referred to as the "*n*-on-*p*" cell. This type silicon cell has shown from 3–50 times better radiation resistance to electrons and low-energy protons (10 MeV) than its *p*-on-*n* counterpart. However this advantage seems to decrease as the proton energy is increased. Normally, one would expect the damage effect of protons to decrease as their energy increased due to the usual Rutherford scattering energy dependence. However the damage rates at very high energies (700 MeV) seem to be several orders of magnitude greater than what would be predicted from the low-energy data. Radiation damage measurements on GaAs solar cells indicate more radiation resistance than in the silicon cells. However this (and in fact all) the radiation damage data must await more refined measurements before definite conclusions are made.

(*f*) *Applications*

If one considers that at Earth there is about 140 mW/cm of solar power available, one can conservatively expect about 14 mW/cm^2 or 140 W/m^2 from a solar-cell power system. It would thus require about 21 m^2 for a 3 kW power supply. This is considered an arbitrary upper limit to what is practical, using present-day solar cells (10^5 cells would be required for 3 kW). For space applications, some sort of unfurlable array would be required to get the cells out of the Earth's atmosphere. When larger-area cells become available, the practical problem associated with these large arrays will become simpler.

In any solar applications where power may be required continuously a storage battery system is required. At present, nickel–cadmium cells are the most practical for solar-cell power storage. These devices are heavy and have reliability problems discussed elsewhere in this paper. It is evident that, with a storage battery system, a solar cell array must be over-designed to maintain a given average output power. For example, the 3 kW system mentioned above may require 25 per cent additional solar cells, so that the storage batteries are properly charged when the sunlight is available. The number of extra solar cells depends on the power level and the light/dark ratio. An additional difficulty arises when cell degradation can take place since a certain minimum output level is required to maintain the storage battery charge. For example a pure solar-cell 3 kW system may have degraded to 2 kW and still supply power when sunlight is present, but the same system with storage batteries might be defunct since the 2 kW is not now sufficient to maintain the minimum charge required by the storage batteries.

In general, a solar-cell system of up to 3 kW power level can be used for communication, navigation, cloud cover and weather surveillance and scientific instrumentation.

(*g*) *Future progress*

The chief disadvantages of present-day solar-cell systems are the cost, weight and complexity. The efficiency and reliability for space applications are better than is available from any other energy conversion device. The reliability is in fact quite good for applications which do not require over 3000 hours in the lower Van Allen Belt.

The most promising future device is the large-area deposited-film type of cell. Considerable progress has already been made in this direction using cadmium sulfide evaporated layers. These cells have exhibited 3·5 per cent conversion efficiency, are extremely light in weight and are large-area devices which presumably could be coated onto existing structures. It has in fact been possible to convert evaporated cadmium sulfide films into single crystals by a simple processing technique. A solar cell made from such films should be about 8 per cent efficient. Such devices should be inherently inexpensive since no single crystal growing, cutting and processing would be required. This development should be practical in the 1963–65 time period.

Single-crystal devices using high quality Si and GaAs with specially treated surface (expensive) should yield efficiencies in the 15–20 per cent range within the 1963–65 time period.

Organic semiconducting films showing a strong photovoltaic effect with about 5–10 per cent efficiency should be available in the 1964–67 time period. Such films would be very inexpensive and may be practical for use to complete with other, more-expensive power sources in areas where sunlight is abundant.

3. THE PHOTOELECTRIC EMISSION CONVERTER

The appeal of a photoelectric emissive converter [3] is that it is basically a large-area device which should be low in cost and light in weight. In operation, one has a photoemissive substance which is directly exposed to sunlight. Electrons are given off and collected by a grid or transparent electrode. A load is connected between the photoemitter and the collector and power is developed, thus completing the conversion of the solar radiation directly into electricity.

There are two basic modes of operation of this type of device, one where the emitted electrons are collected by virtue of their initial velocities, in which case the lowest work function emitter and collector are used. The second mode of operation involves collection by a field produced by a difference in work function between the emitter and the collector. In this case, the lowest work function material is the collector, while the emitter is somewhat higher in work function. The voltage of the device is set by the difference in the work functions which can be between 1/2 and 1 V. In the first mode of operation, the voltage will be of the order of kT as is given by the initial velocity distribution. From the viewpoint of efficient energy conversion, the latter mode is the preferred one. This is because the most efficient photoelectric emitter does not have the lowest work function. Thus, while the Ag–O–Cs emitter has the lowest work function known, 0·75 eV, it has a poor maximum quantum efficiency of 0·005. The $Cs(NaK)_3Sb$ emitter has a work function of 1·55 eV, but a maximum quantum efficiency of 0·4. It can be seen that Ag–O–Cs would be an ideal low-work-function collector, while the $Cs(NaK)_3Sb$ would be an ideal emitter. This combination would give a maximum voltage per cell of about 0·8 V.

The basic limitation of the photoemissive device is its long wavelength threshold. Well over 50 per cent of the solar photons cannot cause the emission of an electron in the best photoemitter. For example, in the above-cited high efficiency emitter, the efficiency is only 10 per cent at 2·4 eV. Only 13 per cent of the sun's spectrum in the outer atmosphere would yield a quantum efficiency greater than 10 per cent. The longer wavelengths contribute negligibly. Neglecting other losses, it is obvious that a top conversion efficiency of about 1–2 per cent is all that can be achieved. Using the method in mode 1, that of the initial velocities, the efficiency can be shown to be an order of magnitude less with the best emitters.

There are two ways in which this efficiency can be improved: (1) to devise a wavelength converter so that the total energy in the solar spectrum is composed of photons of energy greater than 2·5 eV; or (2) devise more efficient photoemitters with thresholds at longer wavelengths. At present it is considered remarkable when wavelength conversion is achieved and no mention is made of efficiency. The process must be at least 50 per cent efficient over the whole spectrum in order to be of use in the instant application. There is little hope for this.

Similarly, much improvement in photoemitter characteristics is not to be expected. This is a field that has been worked over for at least 30 years and progress has been sporadic. The breakthroughs have been due to empirical experimentation rather than that of the basic understanding. One might expect that, for example, the Ag–O–Cs surface will be made more efficient in yield but not in threshold or that the $Cs(NaK)_3Sb$ surface be lowered in threshold but not in yield. However, the experts in the field do not anticipate the kind of improvement required to give a photoemissive device of even 10 per cent overall efficiency. It should be pointed out here that many practical problems not treated would exist such as large area—close space geometry, a collector with low light absorption properties, and the reduction of series resistance in the surface and collector.

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FUEL CELLS

J. B. FRIAUF*

MECHANICAL and electrical energy are the most convenient forms of energy for many applications. Unfortunately, however, they are also energy forms poorly adapted to storage and transport. See Table 1.

TABLE 1. kWH/LB FOR DIFFERENT FORMS OF ENERGY STORAGE

Form of energy storage	kWh/lb
Electrical†	$1{\cdot}9 \times 10^{-6}$
Mechanical‡	$1{\cdot}1 \times 10^{-2}$
Thermal§	$4{\cdot}6 \times 10^{-1}$
Chemical‖	$1{\cdot}6$
Nuclear¶	$1{\cdot}0 \times 10^{7}$

† Capacitor: 14·9 μF; 7500 V; 61 lb.
‡ Flywheel rim: Rocoloy 270; 200,000 p.s.i. working stress; 488 lb/ft^3.
§ Lithium fluoride: thermal energy liberated in cooling from 1500°K to 298°K. Yields $3{\cdot}0 \times 10^{-1}$ kWh/lb of mechanical energy if converted to mechanical energy by a perfect heat engine working between the temperature of thermal energy liberation and 298°K.
‖ Hydrogen plus oxygen: free energy of formation of liquid water.
¶ Uranium 235: fission energy.

For the transport of considerable energy in a reasonable weight we must carry chemical or nuclear energy and convert to electrical or mechanical energy as needed. This is, of course, precisely what we have long been doing with chemical energy, not quite so long with nuclear. Henceforth, it will be assumed that we carry chemical energy and that the end product we desire is electrical energy. The energy conversion steps in three devices which can be used to convert from chemical to electrical energy are:

Central power station: CHEMICAL → THERMAL → MECHANICAL → ELECTRICAL

Thermoelectric generator: CHEMICAL → THERMAL → ELECTRICAL

Fuel cells: CHEMICAL → ELECTRICAL

GENERAL CHARACTERISTICS OF FUEL CELLS

A fuel cell is an electrochemical device for the direct conversion of chemical to electrical energy. In this it resembles a flashlight battery cell, which does the same thing, and, like the flashlight battery cell, gives roughly 1 V per cell. The difference is that the fuel and oxidant that supply the chemical energy are stored within the flashlight battery cell but are stored outside the fuel cell and fed to it as needed. For this reason the fuel cell is also known as a continuous feed primary battery.

Now compare the fuel cell with two other energy converters which also give electrical

* Bureau of Ships, Department of the Navy, Washington, D.C., U.S.A.

energy as the end product, (1) a heat engine plus an electric generator, and (2) a thermoelectric generator. The energy input to both is thermal energy, thus requiring a preliminary conversion from chemical to thermal energy; both must operate between a high temperature, T_1, and low temperature T_2; and both necessarily have an efficiency not greater than the Carnot efficiency, $(T_1 - T_2)/T_1$.

For the fuel cell, on the other hand, the input is not thermal but chemical energy, specifically, $-\Delta G$, which is also frequently written as $-\Delta F$, the decrease in the Gibbs free energy which occurs when the fuel and oxidant react in the fuel cell; operation is at a single temperature, which may be high or low; and the efficiency is not limited to Carnot cycle efficiency. The free energy efficiency is:

$$e = \frac{\text{electrical energy output}}{-\Delta G} \tag{1}$$

The theoretical upper limit is 100 per cent, a figure which has been closely approached in the laboratory. The actual free energy efficiency for fuel cells used for power production will depend upon the kind of fuel cell and the condition of operation and should be from 60–80 per cent or even better.

The decrease in Gibbs free energy is one measure of chemical energy, but not the only one. Another is the heat of reaction, $-\Delta H$, which enters into some expressions for the efficiency of heat engines and fuel cells. Since ΔG and ΔH are not equal, efficiency comparisons may be misleading unless the kinds of efficiency compared are kept clearly in mind. For this reason, it is perhaps better to make comparisons on the basis of specific fuel consumption, that is, lb of reactant per kWh. The theoretical specific weight of reactant for a fuel cell is:

$$w_t = \frac{1{\cdot}895\, nM}{-\Delta G} \tag{2}$$

where ΔG is the free energy change (in kg cal per g mol. wt.) for the chemical reaction in the fuel cell, M is the molecular weight of the reactant, and n is the number of moles of the reactant used in the reaction. For $H_2 + 0{\cdot}5O_2 \rightarrow H_2O$ (liquid) at room temperature, $-\Delta G$ is 56·69. For hydrogen, n is 1, and M is 2·016, hence, we need 0·0673 lb of hydrogen per kWh. For oxygen, n is 0·5 and M is 32, hence, we need 0·535 lb per kWh, or a total for both reactants of 0·602 lb per kWh. This is the theoretical figure for 100 per cent free energy efficiency. The actual weights will be:

$$w_a = \frac{w_t}{e} \tag{3}$$

For many fuels, the weight needed per kWh is roughly half as much as would be needed by an energy converter having the efficiency of a very good central power station. This is, of course, one of the main reasons for the interest in fuel cells. It opens up two attractive possibilities:

(a) Cutting down on the amount of fuel that must be sent to isolated power stations at the far corners of the earth or up in space; and
(b) Conserving our fossil fuel supplies which are being used at an ever increasing rate.

The essential components of a fuel cell are shown in Fig. 1, (a) two electrodes, a fuel electrode or anode and an oxidant electrode or cathode; (b) an electrolyte; and (c) a supply

of fuel and oxidant. The fuel may be hydrogen, a metal, an alcohol, a hydrocarbon, or some other substance which can be oxidized, that is, can lose electrons in a chemical or electrochemical reaction. The oxidant may be oxygen, chlorine, bromine, or some other substance which can be reduced, that is, can gain electrons.

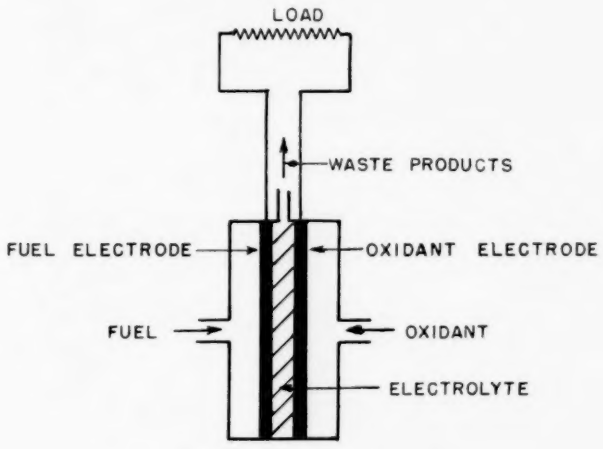

FIG. 1. Fuel cell (direct type).

If the fuel is hydrogen and the oxidant is bromine, the reactions are:

$$\text{At the fuel electrode:} \quad H_2 \rightarrow 2H^+ + 2e^- \tag{4}$$

$$\text{At the oxidant electrode:} \quad Br_2 + 2e^- \rightarrow 2Br^- \tag{5}$$

$$\text{Overall} \quad H_2 + Br_2 \rightarrow 2HBr \tag{6}$$

At the anode or fuel electrode, one molecule of hydrogen gives two positively charged hydrogen ions and two electrons. The two electrons pass through the load connected to the terminals of the cell, supplying electrical energy to it, and arrive at the cathode, or oxidant electrode, where they combine with bromine to give two negatively charged bromine ions. The hydrogen and bromine ions combine to make hydrogen bromide. The net result is to supply electrical energy to the load and combine hydrogen and bromine to make hydrogen bromide.

If oxygen is the oxidant instead of bromine, the cell reactions are more complicated because of the formation and decomposition of the peroxide ion at the oxygen electrode, but the end result is the formation of water and the production of electrical energy. Whatever the fuel and oxidant, the end result of the reactions in a fuel cell is the combination of fuel and oxidant to form one or more reaction products, produce electrical energy, and liberate heat, or, if some rather unlikely fuels and oxidants were to be used, absorb heat from the surroundings when the process is conducted reversibly.

The electrolyte may be aqueous or non-aqueous, the pressure and temperature may be high or low, and fuel utilization may be direct or indirect.

These variations, combined with the variety of possible fuels and oxidants, lead to the rather bewildering array of fuel cells which have been described in recent reviews [1, 2, 3, 4].

To bring some sort of order into this array, fuel cells have been classified in different ways, one being whether direct or regenerative (indirect). We shall consider first the regenerative fuel cells which are currently of interest for space applications and then take up the direct types of fuel cells which are of more interest for terrestrial applications.

REGENERATIVE FUEL CELLS

In the regenerative fuel cells, an intermediate fuel and oxidant are combined in a fuel cell to produce electrical energy and the product of the reaction is treated to regenerate the intermediate fuel and oxidant for another cycle through the fuel cell. Regeneration may be chemical, photochemical, thermal, or electrical.

Chemical regeneration. The intermediate fuel and oxidant are regenerated by reaction with a primary fuel and oxidant. The chemically regenerated fuel cell shown in Fig. 2 has

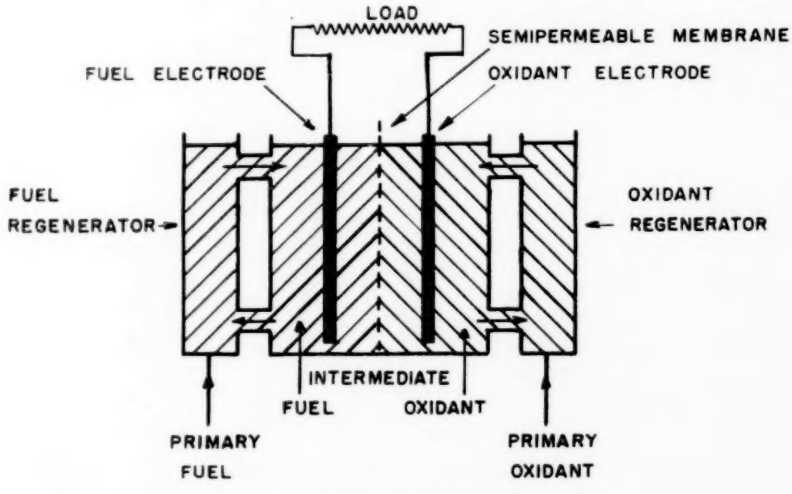

FIG. 2. Chemically regenerated fuel cell system.

regenerators for both fuel and oxidant. Obviously we can use a regenerator for only one and then have what might be called a half regenerative cell. Chemically regenerated fuel cells are also known as Redox fuel cells because of the alternate reduction and oxidation of the intermediate fuel and oxidant as they go through their cycle. A disadvantage of this type of fuel cell is that there is some loss of chemical energy in the regenerators so that the theoretical fuel consumption will be greater than for a direct cell using the same primary fuel and oxidant. There are advantages to compensate for this, but as yet, at least so far as I know, the chemically regenerated fuel cell is lagging behind the direct types.

Photochemical regeneration. The product of the reaction is photochemically dissociated and fuel and oxidant are separated for reuse in the fuel cell. Fuel cells of this type have been proposed for the conversion of solar energy to electrical energy [5, 6].

Thermal regeneration. In a thermally regenerated fuel cell, Fig. 3, a fuel and oxidant are reacted in a fuel cell at a low temperature. The product of the reaction is heated to a high temperature in a heat exchanger and then thermally dissociated to give back the fuel

and oxidant which are separated, cooled in the heat exchanger, and sent back through the fuel cell. In this type of fuel cell, the energy input is not chemical energy but thermal, and the efficiency cannot exceed the Carnot cycle efficiency. The direct types of fuel cells should have higher efficiency if chemical energy is available to start with, and it does not appear that the thermally regenerated fuel cell will be of much interest when this is the case. The situation is different, however, when the input energy source is thermal energy, from solar or nuclear energy for example. In one of the thermally regenerated fuel cell systems which has been proposed, lithium and hydrogen are reacted in the fuel cell to produce electrical energy and form lithium hydride which is thermally dissociated to regenerate the reactants [7].

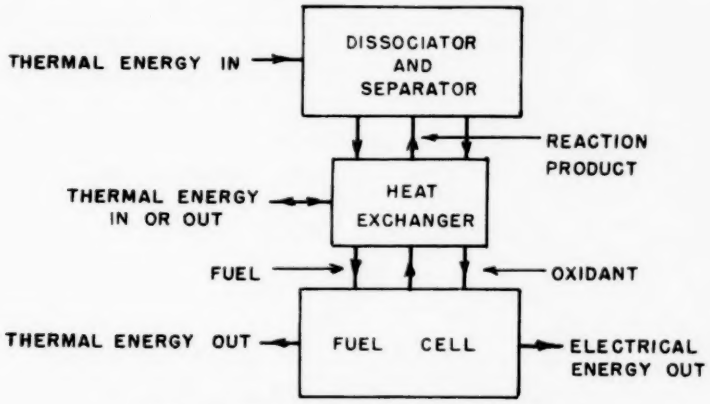

FIG. 3. Thermally regenerated fuel cell system.

Electrically regenerated. The fuel and oxidant are regenerated by passing a current through the cell in the direction opposite the current direction when the cell is supplying power. These cells are thus a special type of storage battery cell and are being studied for space applications where they may have advantages over conventional storage batteries [8, 9].

DIRECT TYPES OF FUEL CELLS

The direct types of fuel cells are those in which the fuel and oxidant are fed directly into the fuel cell and the product of their reaction is disposed of as waste (see Fig. 1). Grouped according to the electrolyte used they include:

1. *Aqueous electrolyte fuel cells*
   (a) Low temperature, low pressure (room temperature to about 100°C, a few atmospheres) [10].
   (b) Medium temperature, high pressure (about 200°–300°C, 20 atm or higher) [11].

2. *Ion exchange membrane electrolyte* [8, 12, 13, 14, 15]

3. *Fused salt, electrolyte (high temperature, about 500°C and higher)*
   (a) Free liquid [16, 17].
   (b) Fused salt in ceramic matrix [16, 18].

4. *Other electrolytes*

As yet of minor importance.

Different fuel cells will be needed for different jobs, but the fuel cell which would bring the greatest joy to the greatest number of hearts is one which would use a cheap hydrocarbon fuel directly in the fuel cell with air as the oxidant when air is available and oxygen when air is not, and would do this in an aqueous electrolyte at low temperature and pressure. We do not yet have this fuel cell. Let us look at those listed above and see how they fall short of what we would like.

Fused salt, high temperature fuel cells

These have been the most successful in using hydrocarbons. Cells of this type could be run continuously for several months, operating between 550 and 700°C on town gas, hydrogen, carbon monoxide, and natural gas [18]. Kerosene vapor at 650°C has been found to give almost the same performance as hydrogen [16]. These are the fuel cells which may ultimately develop into fuel cell central power stations of the future, but the prevention of heat loss from a high temperature installation becomes increasingly difficult as the size is reduced, hence, it would appear that the high temperature fused salt fuel cell is inherently better adapted to large power units than to the medium and small power units of more immediate interest.

Ion exchange membrane fuel cells

These use a solid rather than a liquid electrolyte, the solid being an ion exchange membrane which may be either of the anion or cation type. It has also been proposed to use two ion exchange membranes, one next to each of the two electrodes, with an aqueous electrolyte between the two membranes [15]. The ion exchange membrane is a relative newcomer to the fuel cell field but already shows signs of promise. Portable, 200 W power supplies with ion exchange membrane fuel cells are being developed for use by the Department of Defense. The Bureau of Ships expects to have two of these units delivered early in 1961. These will use a cation exchange membrane as electrolyte, air as oxidant, and hydrogen, generated by the action of a sulphuric acid solution on sodium borohydride, as fuel [14].

Aqueous electrolyte fuel cells with carbon containing fuels

Hydrogen is the most readily utilized fuel for aqueous electrolyte fuel cells, as indeed, it seems to be for most fuel cells. Hydrogen is not, however, a fuel which is either particularly cheap or easy to carry, and for this reason the use of carbon and hydrogen containing fuels in aqueous electrolyte fuel cells is being studied. Some degree of success has been obtained with alcohols, aldehydes, and other organic compounds containing carbon, hydrogen, and oxygen [13, 19]. Hydrocarbons are also being investigated, but much of the work in this area is being done by companies with proprietary interests and relatively little scientific information is available in the public domain. The problems encountered with the use of carbon containing fuels in an aqueous electrolyte include: (a) incomplete oxidation, leading to a loss of efficiency and the build up of intermediate reaction products in the electrolyte; (b) the carbonation of alkaline electrolytes; and (c) the poor performance with acid electrolytes which should by-pass the carbonation problems associated with alkaline electrolytes.

Aqueous electrolyte with hydrogen or metal fuel

The fuel cells which appear to be closest to practical use for power generation in the kW and hundreds of kW range are low temperature and pressure, aqueous electrolyte fuel cells using hydrogen or sodium as the fuel and oxygen (or air) as the oxidant. The Bureau of Ships has contracts for the development of two different types of cell suitable for use in submarines, each type having a power output of about 1 kW per cell.

One is a hydrogen–oxygen fuel cell using a solution of potassium hydroxide as the electrolyte. The oxygen would be carried as liquid oxygen. Hydrogen can be carried as liquid hydrogen but the low density of liquid hydrogen and the hazards associated with it are such that less objectionable methods are being sought.

The other is a sodium amalgam–oxygen fuel cell with an aqueous solution of sodium hydroxide for electrolyte. The fuel electrode is a steel plate over which sodium amalgam is flowed. Spent amalgam is collected at the bottom, enriched with sodium, and recirculated. The mercury in the amalgam is recycled without loss. Sodium is consumed at the fuel electrode, oxygen at the oxygen electrode, and sodium hydroxide is formed. Continuous removal of electrolyte and addition of water keep the sodium hydroxide concentration of the electrolyte at the desired value.

The estimated performance of these fuel cells (for power plants in the several hundreds of kW range) are given in Table 2. It is to be emphasized that these are estimates only and are not based on plants which have been built and tested.

TABLE 2. ESTIMATED PERFORMANCE OF LOW TEMPERATURE, LOW PRESSURE, HYDROGEN–OXYGEN AND AMALGAM–OXYGEN FUEL CELLS

	Hydrogen–oxygen	Amalgam–oxygen
V per cell	0·94	1·80
Pressure (atm)	1–5	1
Weight* (lb/kW)	160	310
Volume* (ft^3/kW)	2·8	2·7
Fuel (lb/kWh)	0·094	1·0
Oxygen (lb/kWh)	0·74	0·36
Total, fuel + oxygen (lb/kWh)	0·834	1·36
Operating cost ($/kWh)	0·07	0·21

* Cells and auxiliaries, but not fuel and oxygen storage tanks.

TRENDS IN FUTURE DEVELOPMENT

Two distinct directions of future development are already clearly indicated. These are:

(a) The development of fuel cells using exotic fuels for special applications (military or space) where fuel cost is not a primary consideration. The sodium amalgam–oxygen fuel cell and the ion exchange membrane portable power supply using hydrogen generated from sodium borohydride are two examples of developments in this direction.

(b) The development of fuel cells for use in applications where fuel cost is an important or controlling consideration. The high temperature fused salt fuel cell is an example of a development in this direction.

Another development in this direction is the use of cheap hydrocarbon fuels (or perhaps methanol) in low temperature, aqueous electrolyte fuel cells. The avenues of attack are:

(a) The use of acid electrolytes from which the carbon dioxide formed by complete oxidation of the fuel would be evolved as a gas. The result would be a particularly simple installation in which the fuel is fed directly into the fuel cell without any preliminary treatment, and removal of the waste products, carbon dioxide and water, is a relatively simple matter.

(b) The use of alkaline electrolyte fuel cells in combination with either:

  (i) Means for regenerating the electrolyte which will be carbonated by the carbon dioxide resulting from oxidation of the fuel; or

  (ii) Preliminary reforming of the hydrocarbon or alcohol fuel to produce carbon dioxide and hydrogen followed by separation of the hydrogen which alone would be fed to a hydrogen–oxygen fuel cell.

Neither of these two alternatives seems as attractive in principle as a fuel cell into which the fuel could be fed without preliminary treatment and the waste products removed without regeneration of the electrolyte.

PROBLEMS

One of the difficulties associated with fuel cells using gaseous reactants was pointed out by Grove [20] more than a century ago, as follows:

> "As the chemical or catalytic action in the experiment described in that paper, could only be supposed to take place, with ordinary platina foil, at the line or water-mark where the liquid, gas, and platina met, the chief difficulty was to obtain anything like a notable surface of action."

We still have with us the problem of obtaining "a notable surface of action" where liquid, gas, and solid meet. One of the advantages claimed for Redox cells is that by suitable choice of reactants the reactions in the fuel cell can be made to take place where only two phases, solid electrode and liquid electrolyte, meet. The same result can also be obtained by using a fuel such as methanol, which can be mixed with the electrolyte.

There is another problem inherent with fuel cells. Their high efficiency is dependent upon conducting the electrochemical processes reversibly. Reversible processes are notoriously slower than irreversible. For the simultaneous attainment of high efficiency and reasonable size of equipment it is necessary to have catalysts which speed up the electrode reactions.

In addition to the above problems there are countless others associated with obtaining equipment which will operate reliably for long periods of time. Many of these problems are of the kind which are sometimes called "mechanical problems" and casually dismissed as being of minor importance. It must be remembered, however, that the solution of minor problems sometimes takes even longer than the solution of a major problem which may vanish almost overnight after a technical breakthrough. For this reason it would be rash to make any predictions as to when fuel cells will become important power sources. That they will come seems certain, when is another matter.

PROSPECTS

When the fuel cell does arrive, its prospects are fascinating. Consider only three fields in which it may be applied.

(1) *Chemical industry*. Substantial amounts of d.c. power are used for electrolysis. Generation of power by fuel cells could lead to significant savings in fuel. Even more intriguing is the possibility of integrating fuel cells into the chemical industry to produce electric power as a by product of reactions that would be carried out in any event. Consider sulfuric acid, for example. Most of it is made by burning sulfur. If the oxidation of sulfur to sulfur dioxide were done in a fuel cell, and if all the sulfuric acid produced in this country were made by burning sulfur, the theoretical amount of electrical energy produced would be almost 2 per cent of the total electrical energy produced in this country or some thirty times the electrical energy needed to make electrolytically all the magnesium produced here. (Figures based on U. S. Production of electrical energy, sulphuric acid, and magnesium in 1959.) There are doubtless other ways in which development of suitable fuel cells could result in the production of a significant amount of electrical energy as a by product of the chemical industry.

(2) *Energy production and storage*. Fuel cells which use hydrocarbon fuels or even coal may become the central power stations of the future. Fuel cells may also find application in systems for the storage of energy obtained from sources which are but little used today, tides, wind, and sun. Finally, fuel cells may ultimately lead to a decline in the importance of central power stations for supplying power to residential consumers. Instead of having electrical energy transmitted to his home, each householder might have in his basement a fuel cell power supply which uses air as the oxidant and as fuel either natural or manufactured gas or a liquid hydrocarbon. Such a plant combined with a heat pump for heating in the winter and cooling in the summer could result in significant savings of fuel. It would be a far cry from conventional central power plants in which the chemical energy of the incoming fuel is split into three roughly equal parts of which only one is usefully employed in the production of electrical energy while the other two are wasted in heating up some body of water.

(3) *Automative vehicles*. A number of companies are interested in fuel cells for fork lift trucks [21]. Delivery trucks are another field of application, and it seems not too much to hope that in the future we may have quiet electric automobiles powered by fuel cells. Fuel consumption should be less, and the fuel cell should also alleviate that part of the smog problem which is caused by the exhaust gases from gasoline powered automobiles.

Summary—The fuel cell is a highly efficient electrochemical device for the direct conversion of chemical to electrical energy. It has not yet been developed to the stage where it is doing any significant part of the world's work, but when it is it should find important application in a world where the increasing population and the increasing energy consumption per capita are making ever and ever greater demands on our fossil fuel supply.

Acknowledgement—It is a pleasure to acknowledge the help of Mr. C. F. Vigolotti of the Electrical Branch, Bureau of Ships.

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MAGNETOHYDRODYNAMIC ELECTRIC POWER GENERATORS

MOSTAFA E. TALAAT*

NOMENCLATURE

$\underline{B}$	Vector magnetic field intensity
B_0	External magnetic field intensity in z-direction
C_p	Specific heat at constant pressure
C_V	Specific heat at constant volume
D	Distance between electrodes
E	Electric field intensity in the y-direction
e	$\dfrac{E}{u_0 B_0}$
$\underline{E}$	Vector electric field intensity
G	Height of generator (distance in z-direction)
J	Current density in minus y-direction
$\underline{J}$	Vector current density
k	Thermal conductivity
L	Length of the generator
S	u/u_0
tr	Trace (tensor operation)
t	Time
U	Internal energy per unit mass
u	Velocity in the x-direction
$\underline{u}$	Vector velocity
u_0	Inlet velocity
V	Terminal voltage
W	Power
w	Power density
x, y, z	Cartesian coordinate system
α	$\dfrac{\gamma - 1}{\gamma} e$
ϵ_0	Dielectric permeability of free space
η	Energy conversion efficiency
θ	$\dfrac{x}{D}$

* The Martin Co., Baltimore, Md. U.S.A.

μ_0 Magnetic permeability of free space
ν Kinematic viscosity
ρ Mass density
ρ_0 Density corresponding to inlet conditions
ρ_q Electrical charge density
σ Electrical conductivity
ϕ $\dfrac{1}{\gamma M^2}$

Subscripts

r Rejection or outlet condition
0 Inlet condition

1. INTRODUCTION

WHEN we examine the electromagnetic induction principle (Fig. 1), we find that a bar, *ab*, of an electrically conducting material moving with velocity, *u*, perpendicular to the lines of an applied magnetic field of intensity, *B*, will have an electric field, *Bu*, generated into it in a direction perpendicular to both the magnetic field and the velocity; viz., from *a* to *b*.

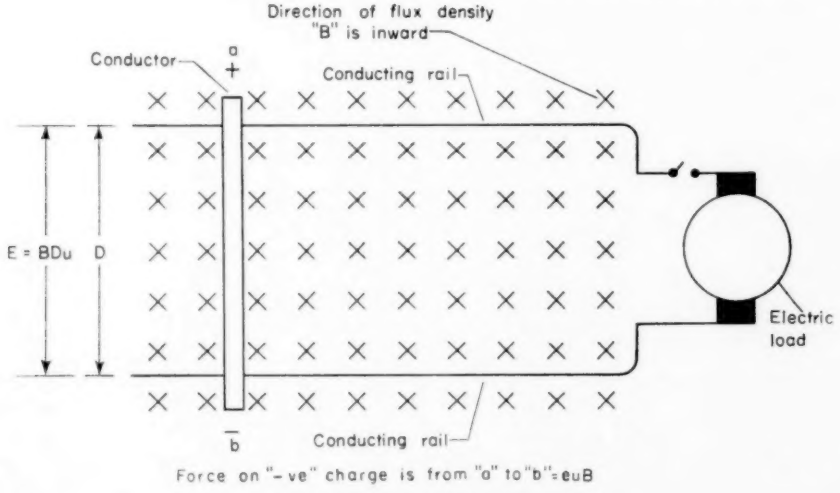

FIG. 1. Electromagnetic induction principle.

The free electrons within the conductor will move in the direction of the field force acting on them, viz., from *a* to *b*, until the accumulation of charges at the conductor ends establishes an electrostatic field intensity *E* equal to the electric field intensity generated by the interaction of magnetic field and the motion. If the moving conductor is made to slide on two conducting rails which are in turn connected to an electric load (see Fig. 1) an electric current flows through the circuit and d.c. electric power is thus delivered to the load.

The dynamoelectric generator operates on the basic electromagnetic induction principle discussed above except that the single conductor sliding on rails is replaced by the more sophisticated design involving a rotating armature with its winding, commutator and brushes.

The arrangement illustrated in Fig. 1 suggests that the conductor does not necessarily have to be a solid. Indeed, if we can replace the solid conductor by the highly conductive plasma of, say, the fusion reaction products (or by any other well-ionized gas or vapor) and, further, if we can make this conductor move at high velocity across a magnetic field, then we can have a method of electric power generation by electromagnetic induction in which the motion of the plasma itself corresponds to the rotation of the armature of a dynamoelectric generator but does not involve heavy moving parts inherent in the use of armatures or turbines. Such a method of conversion is designated by the term magnetohydrodynamic (MHD) energy conversion.

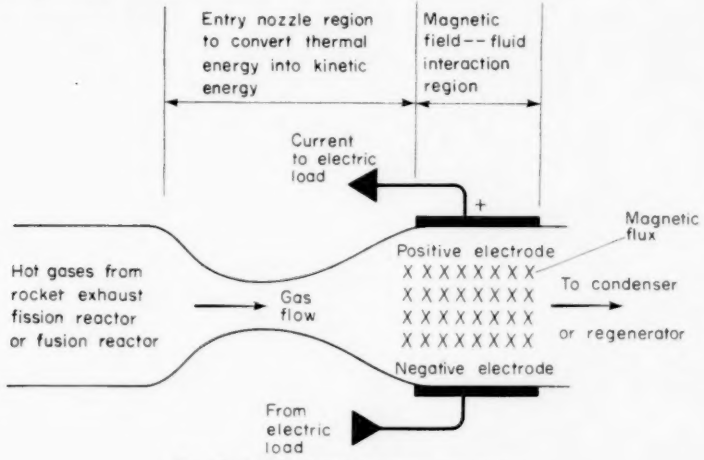

FIG. 2. MHD electric power generator.

In its simplest form, the MHD electric power generator (see Fig. 2) consists of a simple channel having a rectangular cross section. Two opposite walls of this channel serve as the surfaces of the north and south poles of a magnet; the other two walls serve as the electrodes by means of which the electrical current to the load can be extracted. For many applications it is desirable to have an entrance nozzle region to convert part of the total thermal energy to a desired kinetic energy for a prescribed thermodynamic condition at the inlet to the magnetic field-fluid interaction region. Figure 2 schematically illustrates a typical arrangement of an MHD generator.

Thus, the MHD generator offers an advantage over the conventional steam-turbine generator in that it entails a basically simpler design concept; the rotating turbine and rotating dynamoelectric generator are replaced by a single channel through which the working fluid itself is first made electrically conductive, then passed at high velocity across the magnetic field. This arrangement has the potential of taking full advantage of the high-temperature thermal energy sources which are available, or will become available in the future, without the need for any dynamically highly stressed parts operating at the ultra high temperatures (above 2000°K) involved.

Having presented the reasoning behind the emergence of the concept of the MHD electric power generator, and having qualitatively described the principle of its operation, let us present the fundamental theory involved. We can then discuss the performance possible by future and present-day technology and the research problems which face this method of direct conversion and which must be solved before its full potential can be realized.

2. BASIC THEORY

Magnetohydrodynamics [1] is the science dealing with the motion of an electrically conductive fluid under the influence of a magnetic field. The equations governing the behavior of the MHD electric power generator are therefore Maxwell's electromagnetic field equations, the generalized Ohm's law, the hydrodynamic equations modified to take account of the interaction between the motion and the magnetic field, and the energy equation.

Maxwell's equations consist essentially of the following:

(1) The generalized differential expression of Faraday's law for the curl of the electric field, namely,

$$\nabla \times \underline{E} = -\frac{\partial \underline{B}}{\partial t} \tag{1}$$

(2) The generalized differential expression of Gauss' law for the divergence of the magnetic field,

$$\nabla \cdot \underline{B} = 0 \tag{2}$$

(3) The generalized differential expression of Biot and Savart's law for the curl of the magnetic field,

$$\nabla \times \underline{B} = \mu_0 J + \mu_0 \epsilon_0 \frac{\partial \underline{E}}{\partial t}. \tag{3}$$

(4) The generalized differential expression of Gauss' law for the divergence of the electric field,

$$\nabla \cdot \underline{E} = (\rho_q/\epsilon_0). \tag{4}$$

The generalized differential expression of Ohm's law for a moving medium includes, besides the term due to the electric field, E, a term due to the induced electric field, $\underline{u} \times \underline{B}$, resulting from the motion of the medium at velocity, $\underline{u}$, under the influence of the magnetic field intensity, $\underline{B}$, and another term due to the transport of the net charge density, ρ_q, by the medium moving with a velocity, $\underline{u}$:

$$\underline{J} = \sigma(\underline{E} + \underline{u} \times \underline{B}) + \rho_q \underline{u}. \tag{5}$$

The hydrodynamic equations consist of the following:

(1) The differential expression of the mass continuity equation,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \underline{u}) = 0 \tag{6}$$

(2) The differential equation of motion which is essentially a statement of Newton's second law for a differential volume of the moving medium and includes, in addition to body forces due to motion

$$\rho\left(\frac{\partial u}{\partial t} + (\underline{u} \cdot \nabla)\,\underline{u}\right),^{*}$$

the pressure gradient, (∇p), the gravity force, (ρg), the force due to viscosity, $\rho\nu[\nabla^2 \underline{u} + (1/3)\,\nabla(\nabla \cdot \underline{u})]$, an electromagnetic body force term, $(\underline{J} \times \underline{B} + \rho_q \underline{E})$.

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* For coordinate systems other than Cartesian coordinates, replace $(\underline{u} \cdot \nabla)\underline{u}$ by $(\nabla \underline{u})\underline{u}$.

Thus

$$\rho\left[\frac{\partial \underline{u}}{\partial t} + (\underline{u} \cdot \nabla)\,\underline{u}\right] = -\nabla p + \rho g + \rho\nu\,\nabla^2\,\underline{u} + (1/3)\,\rho\nu\nabla(\nabla \cdot \underline{u}) + \underline{J} \times \underline{B} + \rho_q\,\underline{E}. \quad (7)$$

The differential expression for the generalized energy equation for a compressible fluid flow has, in addition to the internal energy term,

$$\rho\left[\frac{\partial U}{\partial t} + \underline{u} \cdot \nabla U\right]$$

where $U = C_V T$† and the term representing the work done by motion,

$$\frac{p}{\rho}\left[\frac{\partial \rho}{\partial t} + \underline{u} \cdot \nabla \rho\right];$$

heat terms per unit volume due to Joule heat $[(1/\sigma)\,J^2]$, due to heat conduction, $(k\nabla^2 T)$, and due to viscosity, $\{(1/2)\,\rho\nu\,\mathrm{tr}[\nabla \underline{u} + (\nabla \underline{u})_*]^2\}$.
Thus,

$$\rho\left[\frac{\partial U}{\partial t} + \underline{u} \cdot \nabla U\right] = \frac{p}{\rho}\left[\frac{\partial \rho}{\partial t} + \underline{u} \cdot \nabla \rho\right] + \frac{1}{\sigma}J^2 + k\nabla^2 T + (1/2)\,\rho\nu\,\mathrm{tr}[\nabla \underline{u} + (\nabla \underline{u})_*]^2 \quad (8)$$

where the asterisk denotes the transpose of the tensor.

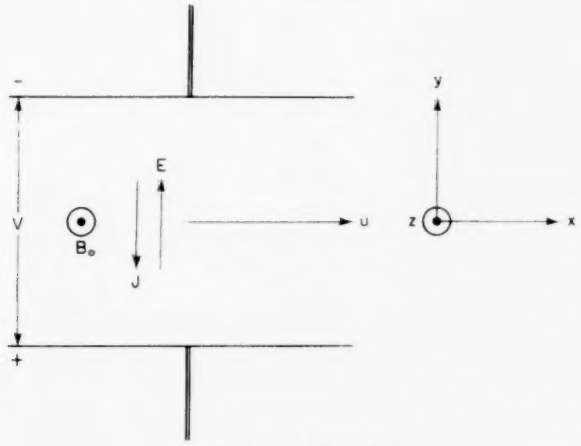

FIG. 3. Coordinate system.

Equations (1) to (8) represent the most generalized equations which govern the performance of the MHD electric power generator under steady-state or transient conditions.

For the sake of simplicity and clarity in understanding the phenomena and in evaluating the potential performance of the MHD generator, let us consider the solution of these equations under steady-state conditions and for the case of a one-dimensional flow of an electrically-conducting gas or plasma inside a duct having a rectangular cross section. We choose the coordinate axes with the plasma flowing with velocity, u, in the x-direction (see

† In general $U = \int_{T_o}^{T} C_V(T)\,dT$.

Fig. 3). An external constant magnetic field, B_0, is impressed in the z-direction, the current density, J, is flowing in the minus y-direction, the terminal voltage, V, exists in the minus y-direction, and the electric field, E, exists in the y-direction. We further make the following simplifying assumptions:

(1) The electrical conductivity of the plasma is a scalar constant.
(2) The fluid flow is strictly one dimensional which means that all variables, in addition to the gas dynamical state variables, vary only in the direction of flow (x-direction) but not over the cross-section of the channel.
(3) The effects of gravity, viscosity or thermal conductivity of the gas are neglected.
(4) The ionized gas or plasma obeys the perfect gas law.
(5) The ratio of specific heat at constant pressure to specific heat at constant volume (γ) is constant.
(6) The ionized gas or plasma flow through the channel is free from shocks; i.e., the flow is free from any regions in which the temperature, pressure and density change very rapidly with distance.
(7) The electrodes are perfectly conducting and extend over the entire magnetic field–fluid interaction length of the channel.
(8) The ionized gas or plasma is electrically neutral.
(9) The voltage drops at the electrode sheaths are small, in comparison with the output voltage, and can be neglected.
(10) The applied magnetic field in the z-direction is constant.
(11) Any currents induced in the direction of flow (x-direction) are negligible compared to the main current induced in the y-direction.

Then, for steady-state conditions and constant cross-sectional area, the general differential equations governing the behavior of the MHD electric power generator (equations (1)–(8) inclusive) reduce to the following scalar differential equations:

$$\frac{dE}{dx} = 0 \qquad \text{i.e., } E \text{ does not vary along the length of the channel} \tag{1a}$$

$$\frac{dB}{dz} = 0 \qquad \text{i.e., } B \text{ does not vary along the magnetic air gap} \tag{2a}$$

$$\frac{dB}{dx} = \mu_0 J \qquad \text{i.e., the variation of } B \text{ along the channel is proportional to the current density } J \text{ (armature reaction effect)} \tag{3a}$$

$$\frac{dE}{dy} = 0 \qquad \text{i.e., } E \text{ does not vary along the distance between the electrodes} \tag{4a}$$

$$J = \sigma(uB - E), \tag{5a}$$

where

$$E = (V/D).$$

$$\frac{d}{dx}(\rho u) = 0, \qquad \text{or } \rho u = \rho_0 u_0 = \text{constant}, \tag{6a}$$

$$\rho u \frac{du}{dx} + \frac{dp}{dx} = -JB, \tag{7a}$$

and

$$\rho u \frac{dU}{dx} = \frac{p}{\rho} u \frac{d\rho}{dx} + \frac{1}{\sigma} J^2, \tag{8a}$$

where

$$U = C_V T.$$

In addition to these equations we introduce the equation of state for an ideal gas,

$$p = \rho RT, \quad \text{where } R = (\gamma - 1)\, C_V = \frac{\gamma - 1}{\gamma}\, C_p, \quad \text{and } \gamma = (C_p/C_V); \tag{9}$$

and the Mach number, M,

$$u^2 = M^2\, \gamma RT, \quad \text{where } \gamma R = (\gamma - 1)\, C_p \tag{10}$$

Differentiating equation (9), with respect to x, and then substituting for $\mathrm{d}\rho/\mathrm{d}x$ into equation (8a), we get the following expression for the energy equation:

$$\rho u \frac{\mathrm{d}}{\mathrm{d}x}(C_V T) = u \frac{\mathrm{d}p}{\mathrm{d}x} - \rho u \frac{\mathrm{d}(RT)}{\mathrm{d}x} + \frac{1}{\sigma} \mathrm{J}^2 \tag{8b}$$

By substituting for $\mathrm{d}p/\mathrm{d}x$ from equation (7a), and since by definition, $C_p = C_V + R$, we get the following expression for the heat equation:

$$\rho u \frac{\mathrm{d}}{\mathrm{d}x}\left(C_p T + \frac{1}{2} u^2\right) = - JuB + \frac{1}{\sigma} \mathrm{J}^2$$

or

$$\rho u \frac{\mathrm{d}}{\mathrm{d}x}\left[\frac{1}{\gamma - 1} \frac{u^2}{M^2} + \frac{1}{2} u^2\right] = - JE. \tag{8c}$$

Equations (3a), (5a), (6a), (7a), (8c), (9) and (10) are seven simultaneous differential equations in seven dependent variables B, J, u, ρ, p, T and M. The solution of these equations will be carried out for the case of nonisentropic flow when the effects on the fluid flow of the magnetic fields produced by the induced current distributions are negligible (similar to saying, in the case of the conventional d.c. generator, that all armature reaction effects are negligible); i.e., when the motion-induced magnetic fields are negligible or the magnetic Reynolds number, $\sigma\mu_0 u_0 L$, is very small such that from equation (3a)

$$\frac{\mathrm{d}(B/B_0)}{\mathrm{d}(x/L)} = (\mu_0 \sigma u_0 L)\left(\frac{J}{\sigma u_0 B_0}\right) \to 0.$$

This is equivalent to saying that the net magnetic field does not vary along the length of the channel. This will be the case when the electrical conductivity is as small as can be practically achieved by present-day techniques of thermal ionization of alkali metals in seeded combustion gases or coolant gases in nuclear reactor cores (σ is on the order of 1 to 500 mho/m).

For this case, the equations governing the behavior of the MHD generator for the unidimensional flow are the six equations (5a), (6a), (7a), (8a), (9) and (10). The six unknowns are J, u, ρ, p, M and T. By eliminating J, ρ, p and T from these equations we get: For the equation of motions,

$$\rho_0 u_0 \frac{\mathrm{d}}{\mathrm{d}x}\left(u + \frac{u}{\gamma M^2}\right) = - JB_0 = - \sigma(uB_0 - E)\, B_0; \tag{11}$$

and for the energy equation,

$$\rho_0 u_0 \frac{\mathrm{d}}{\mathrm{d}x}\left(\frac{1}{2} u^2 + \frac{1}{\gamma - 1} \frac{u^2}{M^2}\right) = - JE = - \sigma(uB_0 - E)\, E. \tag{12}$$

Next we introduce the following dimensionless quantities:

(1) The magnetic interaction number, N_0, to be equal to the product of the magnetic pressure number, N_{mp}, and the magnetic Reynolds number, N_{mr}, we have

$$N_0 = N_{mp}\, N_{mr} = \frac{B_0^2}{\mu_0 \rho_0 u_0^2}\,(\mu_0 \sigma u_0 D) = (B_0^2 \sigma D/\rho_0 u_0) \tag{13}$$

where

$$N_{mp} = \frac{\text{magnetic energy density}}{\text{inlet kinetic energy density}} = \frac{B_0^2}{2\mu_0}\Big/\left(\frac{1}{2}\,\rho_0 u_0^2\right) = \frac{B_0^2}{\mu_0 \rho_0 u_0^2} \tag{14}$$

and

$$N_{mr} \text{ is a measure of the ratio } \frac{\text{motion-induced magnetic field intensity}}{\text{impressed magnetic field intensity}} = \frac{\mu_0 \sigma u_0 B_0 D}{B_0}$$
$$= \mu_0 \sigma u_0 D. \tag{15}$$

(2) $S = \dfrac{u}{u_0} =$ normalized velocity in terms of the inlet velocity. (16)

(3) $\theta = \dfrac{x}{D} =$ normalized axial distance, measured from the inlet plane, in terms of the distance between electrodes. (17)

(4) $e = \dfrac{E}{u_0 B_0} = \dfrac{\gamma}{\gamma - 1}\,\alpha =$ electric efficiency or ratio of load voltage to open circuit voltage. (18)

(5) $\phi = \dfrac{1}{\gamma M^2} =$ Mach number factor. (19)

Then the equation of motion and the energy equation take the following normalized forms, respectively:

$$\frac{\mathrm{d}}{\mathrm{d}\theta}\,(S + S\phi) = -\,N_0(S - e), \tag{20}$$

and

$$\frac{\mathrm{d}}{\mathrm{d}\theta}\left(\frac{\gamma}{\gamma - 1}\,\phi S^2 + \frac{1}{2}\,S^2\right) = -\,N_0 e(S - e). \tag{21}$$

Solution of equations (20) and (21) for ϕ in terms of S, with the boundary condition $\phi = \phi_0 = (1/\gamma M_0^2)$ at $S = 1$, yields

$$\phi = \frac{1}{\gamma M^2} = \frac{\left(\phi_0 + \dfrac{\gamma - 1}{2\gamma}\right) - \alpha(\phi_0 + 1) + \alpha S - \dfrac{\gamma - 1}{2\gamma}\,S^2}{S(S - \alpha)} \tag{22}$$

$$= \frac{(\phi_0 + 0{\cdot}2) - \alpha(\phi_0 + 1) + \alpha S - 0{\cdot}2\,S^2}{S(S - \alpha)} \quad \text{if } \gamma = (5/3) \tag{22a}$$

Substituting for ϕ from equation (22) into the equation of motion equation (20), differentiating with respect to θ and then solving for θ in terms of S, with the boundary condition $\theta = 0$ at $S = 1$, we get

$$N_0\theta = -K_{11}\,\frac{S - 1}{(S - \alpha)\,(1 - \alpha)} - K_{12}\,\ln\left(\frac{S - \alpha}{1 - \alpha}\right) - K_{22}\,\ln\left(\frac{S - e}{1 - e}\right) \tag{23}$$

where

$$K_{11} = f_{11}(a, \phi_0) = \left(\frac{\gamma - 1}{a}\right)\left[\frac{\gamma + 1}{2\gamma}\, a^2 - (1 + \phi_0)\, a + \left(\frac{\gamma - 1}{2\gamma} + \phi_0\right)\right] \tag{24}$$

$$= \left(\frac{2}{3a}\right)[0{\cdot}8\, a^2 - (1 + \phi_0)\, a + (0{\cdot}2 + \phi_0)] \quad \text{if } (\gamma = 5/3); \tag{24a}$$

$$K_{12} = f_{12}(a, \phi_0) = \left(\frac{\gamma - 1}{a}\right)^2\left[\left(\frac{\gamma + 1}{2\gamma}\right) a^2 - (1 + \phi_0)\, a + \left(\frac{\gamma - 1}{2\gamma} + \phi_0\right)\right] \tag{25}$$

$$= \left(\frac{2}{3a}\right)^2 [0{\cdot}8\, a^2 - (1 + \phi_0)\, a + (0{\cdot}2 + \phi_0)] \quad \text{for } \gamma = (5/3); \tag{25a}$$

and

$$K_{22} = f_{22}(a, \phi_0) = \left(\frac{\gamma - 1}{a}\right)^2\left[\frac{2 + \gamma - \gamma^2}{2(\gamma - 1)^2}\, a^2 + (1 + \phi_0)\, a - \left(\frac{\gamma - 1}{2\gamma} + \phi_0\right)\right] \tag{26}$$

$$= \left(\frac{2}{3a}\right)^2 [a^2 + (1 + \phi_0)\, a - (0{\cdot}2 + \phi_0)] \quad \text{for } \gamma = (5/3). \tag{26a}$$

From basic principles, the electrical power output is given by

$$W_e = \int_0^L GD(JE\, \mathrm{d}x). \tag{27}$$

Substituting for $(JE\, \mathrm{d}x)$ from the energy equation (equation 12), we get

$$W_e = -\int_0^L GD\rho_0 u_0 \frac{\mathrm{d}}{\mathrm{d}x}\left[\frac{1}{\gamma - 1}\frac{u^2}{M^2} + \frac{1}{2}u^2\right] \mathrm{d}x$$

$$= (GD\, \rho_0\, u_0)\, u_0^2\left[\left(\frac{\gamma}{\gamma - 1}\,\phi_0 + \frac{1}{2}\right) - \left(\frac{\gamma}{\gamma - 1}\,\phi_r + \frac{1}{2}\right) S_r^2\right] \tag{28a}$$

$$= (GD\, \rho_0\, u_0)\, [(C_p\, T_0 + \tfrac{1}{2}\, u_0^2) - (C_p\, T_r + \tfrac{1}{2}\, u_0^2\, S_r^2)] \tag{28b}$$

$$= (GD\, \rho_0\, u_0)\, [C_p\, T_{S_0} - C_p\, T_{S_r}]. \tag{28c}$$

Inspection of equation (28) shows that the electrical power output is represented by the difference between the total inlet enthalpy, $W_0 = (GD\, \rho_0\, u_0)\, (C_p\, T_0 + \frac{1}{2}\, u_0^2)$, and the total reject enthalpy, $W_r = (GD\, \rho_0\, u_0)\, (C_p\, T_r + \frac{1}{2}\, u_0^2\, S_r^2)$. The expression for efficiency is then obtained by taking the ratio of W_e to W_0, viz.,

$$\eta = 1 - \frac{\dfrac{\gamma}{\gamma - 1}\,\phi_r + \dfrac{1}{2}}{\dfrac{\gamma}{\gamma - 1}\,\phi_0 + \dfrac{1}{2}}\, S_r^2 \tag{29a}$$

$$= 1 - \frac{C_p\, T_r + \frac{1}{2}\, u_0^2\, S_r^2}{C_p\, T_0 + \frac{1}{2}\, u_0^2} \tag{29b}$$

$$= 1 - \frac{T_{S_r}}{T_{S_0}} = \frac{T_{S_0} - T_{S_r}}{T_{S_0}} \tag{29c}$$

It is thus seen from the expression of efficiency that the generator has an efficiency equal to the Carnot efficiency which is characterized by the inlet and exit stagnation temperatures, T_{S_0}, and T_{S_r}, respectively.

The expression for electrical output power density, (w_e), is given by dividing the expression for electrical power output, (W_e), given by equation (28), by the total volume, (GDL), of the magnetic field–fluid interaction section of the duct, viz.,

$$w_e = \left(\frac{\rho_0 u_0}{L}\right) u_0^2 \left[\left(\frac{\gamma}{\gamma-1}\phi_0 + \frac{1}{2}\right) - \left(\frac{\gamma}{\gamma-1}\phi_r + \frac{1}{2}\right) S_r^2\right] \tag{30}$$

$$= \left(\frac{\rho_0 u_0}{L}\right) u_0^2 \left[\frac{\gamma}{\gamma-1}\phi_0 + \frac{1}{2}\right] \eta = \frac{\sigma B_0^2}{N_0 \theta_r} C_p T_{S_0} \eta = w_0 \eta$$

where

$$w_0 = \left(\frac{\rho_0 u_0}{L}\right) u_0^2 \left[\frac{\gamma}{\gamma-1}\phi_0 + \frac{1}{2}\right]$$

is the input power density.

To obtain the exit flow velocity condition which would result in maximum efficiency, we differentiate the efficiency expression (equation 29a) with respect to S_r after substituting the expression for ϕ_r as a function of S_r from equation (22), and equate the result to zero. We get the following expression for the exit velocity, S_r, in terms of the load factor, α, and the inlet Mach number factor, ϕ_0, viz.,

$$S_r = \alpha + \left[\alpha^2 + \frac{2\gamma}{\gamma+1}\phi_0(1-\alpha) + \frac{\gamma-1}{\gamma+1} - \frac{2\gamma}{\gamma+1}\alpha\right]^{1/2}. \tag{31}$$

This expression for S_r is also (by equation 22) the expression for S_r at exit Mach one for any given load factor, (α), and any given inlet Mach number factor, (ϕ_0). In other words, maximum efficiency for any load will always occur when the exit velocity condition corresponds to Mach one; i.e., the thermodynamic choke line, ($\phi_r = 1/\gamma$).

It can also be shown, from equation (22) that for subsonic inlet Mach numbers, ($M_0 < 1$), the normalized velocity $S > 1$, and that for supersonic inlet Mach numbers, ($M_0 > 1$), the normalized velocity $S < 1$. This is of particular significance if we again examine equation (23) which gives the expression for the normalized length, (θ), in terms of the normalized velocity, (S), at any plane along the generator duct. We can see from this equation that if the velocity $S \leqslant \alpha$ or $S \leqslant e$, then the channel length, (θ), goes to ∞ or $-\infty$. Physically, this means that shock waves would occur for these particular load conditions. Since $e \leq 1$ and $\alpha < e$, it follows that S must be $\geq (e \leq 1)$ for a shock-free flow throughout the duct. This is always the case for subsonic inlet Mach number (subsonic flow) where $S > 1$, but is not true under all load conditions for a supersonic inlet Mach number (supersonic flow) where $S < 1$.

3. MAXIMUM EFFICIENCY FOR SUBSONIC-FLOW, CONSTANT-AREA, SINGLE-STAGE MHD GENERATOR

If we substitute the expression for the exit velocity, S_r, as given by equation (31) (with $\phi_r = 1/\gamma$) into the expression for efficiency as given by equation (29a) we get the following expression for the efficiency in terms of the inlet Mach number factor, (ϕ_0), and the load factor, (α):

$$\eta = 1 - \frac{\dfrac{\gamma}{\gamma-1}\dfrac{1}{\gamma} + \dfrac{1}{2}}{\dfrac{\gamma}{\gamma-1}\phi_0 + \dfrac{1}{2}}\left[\alpha + \left\{\alpha^2 - \frac{2\gamma}{\gamma+1}\alpha + \frac{\gamma-1}{\gamma+1} + \frac{2\gamma}{\gamma+1}\phi_0(1-\alpha)\right\}^{1/2}\right]^2. \tag{32}$$

By differentiating with respect to ϕ_0, we find that for subsonic flow the maximum occurs at input Mach number zero, and that under these conditions the ultimate conversion efficiency for the generator is $\gamma - 1/\gamma$ times the electric efficiency, e, i.e., the ultimate efficiency of the subsonic MHD generator with a monatomic plasma cannot exceed 40 per cent of the electrical efficiency, viz., 40 per cent of the ratio of load voltage to open circuit voltage (voltage at an infinite load resistance).

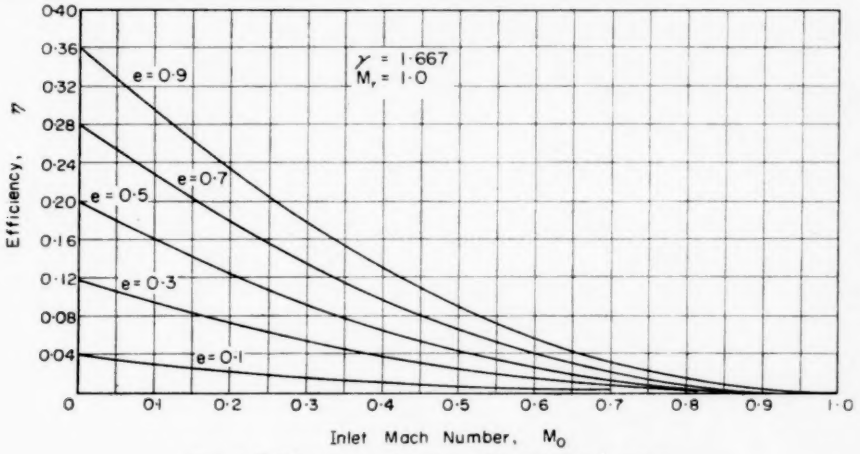

FIG. 4. Efficiency as a function of inlet Mach number.

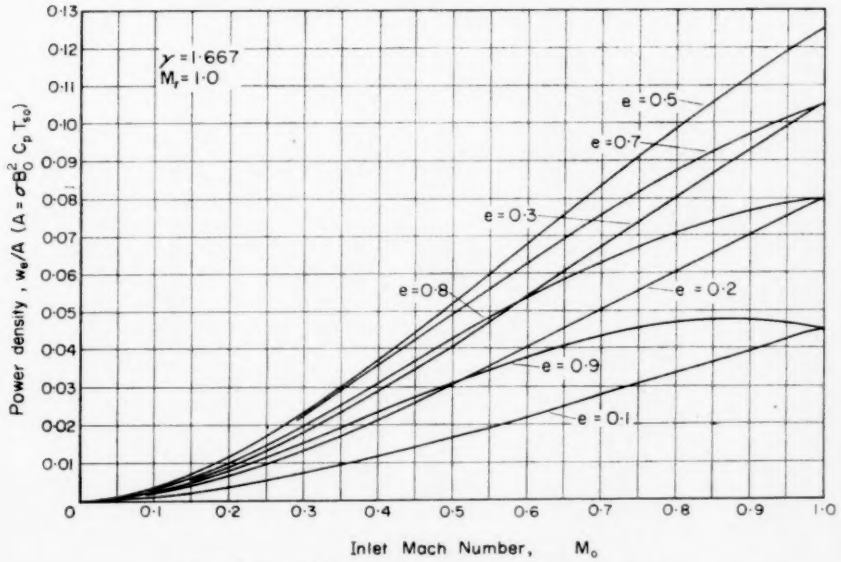

FIG. 5. Effect of inlet Mach number on power density.

But the equation for S, in terms of $N_0\,\theta$, tells us that inlet Mach zero means a generator of infinite length; hence, zero power density. However, if we take the more realistic case of an inlet Mach number of 0·1, and an electric load voltage to open circuit voltage ratio of 0·88, the conversion efficiency drops to 28·6 per cent.

In Figs. 4 and 5, we present curves showing the variation of efficiency and normalized output power density versus inlet Mach number for a fixed exit Mach one and at various output to open circuit voltage ratios ($e = 0{\cdot}1$, $0{\cdot}3$, $0{\cdot}5$, $0{\cdot}7$ and $0{\cdot}9$). The power density curves are normalized with respect to ($B^2 \sigma C_p T_{S_0}$).

Note that for all load conditions the efficiency continuously drops with an increase in inlet Mach number, but that the output power density reaches a maximum for $e = 0{\cdot}9$ at inlet Mach $0{\cdot}875$. For other values of e, there is no output power density maximum but with the highest value of power density occurring at inlet Mach one.

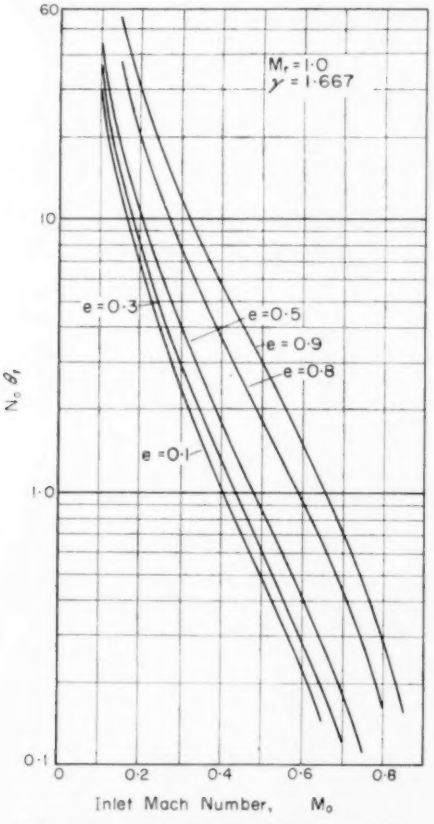

FIG. 6. Length to reach Mach 1·0 at outlet

In addition, for the reader's convenience, we have used the equations presented in this paper to obtain normalized plots of the following useful quantities important in the design and calculation of MHD generator performance.

Figure 6 gives plots for the normalized length, $N_0\,\theta$, of the MHD generator as a function of input Mach number and for various values of e($e = 0{\cdot}3$, $0{\cdot}5$, $0{\cdot}8$ and $0{\cdot}9$: see equation 23).

Figure 7 gives plots for the normalized reject temperature as a function of input Mach number and for various values of e($e = 0{\cdot}1$, $0{\cdot}3$, $0{\cdot}5$, $0{\cdot}8$ and $0{\cdot}9$: see equation 28(b)).

Figure 8 gives plots for the normalized exit velocity as a function of inlet Mach number

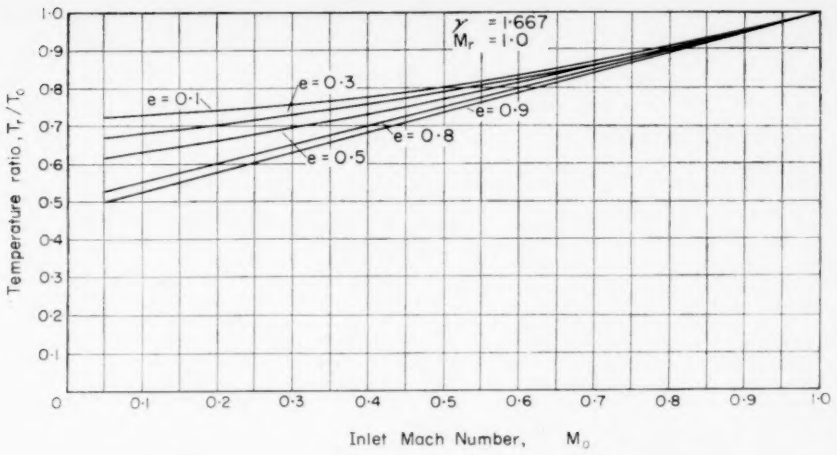

FIG. 7. Dependence of temperature ratio on inlet Mach number.

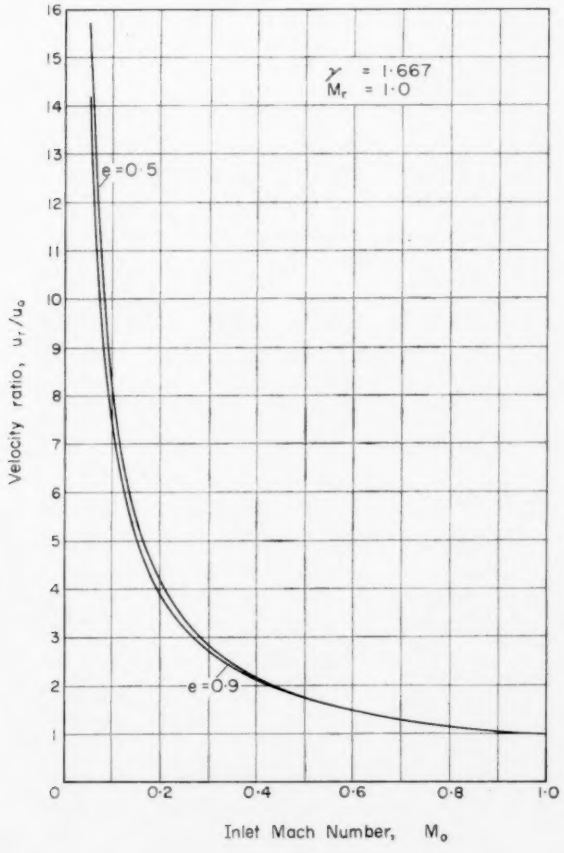

FIG. 8. Velocity ratio vs. inlet Mach number.

and for ($e = 0{\cdot}5$ and $e = 0{\cdot}9$: see equation 31). It is apparent from these exit velocity plots that the exit velocity is not a very sensitive function of load.

Figure 9 gives plots of the normalized exit pressure ratio as a function of inlet Mach number $e = 0{\cdot}3$ and $e = 0{\cdot}9$. Again it is apparent from these pressure plots that the exit pressure is not a very sensitive function of load.

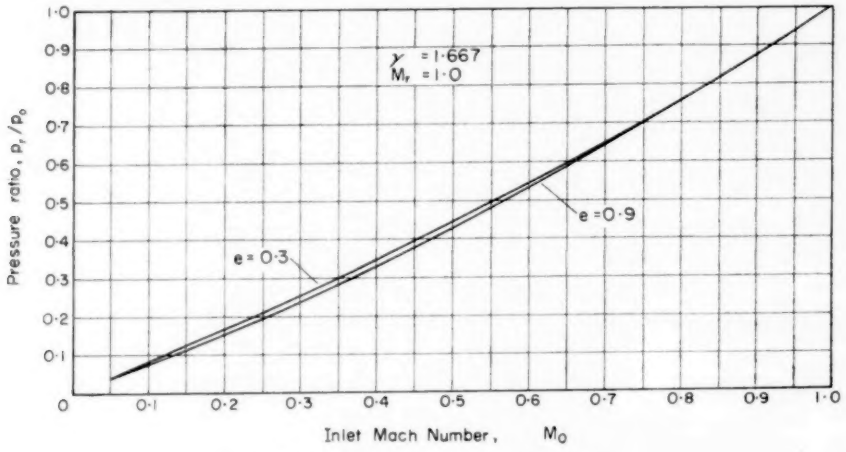

FIG. 9. Pressure ratio vs. inlet Mach number.

Let us pause here for a moment and remember that in the calculations leading to the efficiencies quoted we have neglected:

(1) The power necessary for electric field excitation which must be maintained at a low percentage of the output (say 1–5 per cent compared to 1 per cent for a conventional dynamoelectric generator).
(2) The loss due to viscosity, thermal conduction and radiation from the plasma.
(3) The Joule losses in the electrical leads, and any losses due to thermal conduction through the electrical leads. This degradation loss, and that of (2), above, can be limited by proper design, possibly to 10 per cent of the total output.
(4) The thermal energy necessary to raise the temperature of the cathode electrode to permit the electrons constituting the load current and flowing from cathode to plasma to overcome the cathode-surface work-function barrier.
(5) The losses due to energy which must be spent by the electrons, constituting the load current and flowing toward the anode, in order to penetrate the work-function potential barrier at the anode electrode. This loss is very similar to the cathode work-function loss and is of the same order of magnitude (a high anode work function is desirable to minimize back-emission current).
(6) End losses which occur in the form of eddy currents as the fluid passes into and out of the magnetic field–fluid interaction region.

4. DISCUSSION

So far, we have discussed the reasoning behind the emergence of the MHD electric power generator concept and its ultimate heat source or sources. We have also presented the expression for efficiency and power density and shown that the theoretical limit on the

heat to electricity conversion efficiency is 40 per cent for a single-stage subsonic machine of a constant cross-section and an infinite length supplying an infinite resistance load. We have also assessed the various losses which can occur but which were neglected in this fundamental analysis.

In addition, we have shown that the power density decreases with increase in efficiency, and that for the condition of exit Mach one there exists for the load factor $e = 0{\cdot}9$ an inlet Mach number (0·875) at which an optimum power density occurs. Finally, we have shown that for given geometry, load inlet, and exit Mach numbers, the power density is directly proportional to the square of the magnetic field intensity, the electrical conductivity, the specific heat at constant pressure, and the inlet stagnation temperature.

These latter quantities, together with the necessity of extracting large current densities from the cathode for the large power density requirement, possess all the elements of the problems facing research workers in the field of magnetohydrodynamic energy conversion: problems which must be solved before the MHD generator can realize its full potential.

The magnetic field intensity is usually limited by the power requirement for the magnet field coils which, for an MHD generator employing magnetic metal poles, is mainly determined by the spacing between the north pole and south pole faces of the magnet which in turn must be large enough to prevent viscous effects from becoming important.

For very small generators with output capacity of 1 to 100 kW, permanent magnets or electromagnets may be used, but these must be cooled to temperatures below their magnetic material curie point. With permanent magnets there is no power consumption, while with electromagnets the power consumption in the coils may be limited to 25 per cent of the power output for MHD generators having capacities of the order of hundreds of kW. For MHD generators having capacities of the order of hundreds of thousands of MW and air gaps on the order of a foot, air-core electromagnets are visualized. The order of magnetic field intensities realizable with these arrangements range from 0·5 Wb/m^2 or 5000 G to 2 Wb/m^2 or 20,000 G. Magnetic field intensities on the order of 10 Wb/m^2 or 100,000 G are a research goal* both for this field and that of fusion reaction.

The desirability of high electrical conductivity, high specific heat at constant pressure, and high inlet stagnation temperature in order to raise the output power densities to the order of tens or hundreds of MW/m^3, as well as the requirement of producing high emission-current densities from the cathode (on the order of millions of amp/m^2 or hundreds of amp/cm^2), embodies the following problems which are most difficult to solve:

(1) How to maintain the structural strength, thermal insulation and electrical insulation properties of the channel containing the ionized gas or vapor flow at temperatures ranging from 2000°–5000°K, without excessive oxidation or evaporation of the channel material.

(2) How to efficiently ionize a gas or vapor having a high specific heat, hence a low atomic weight and a high ionization potential. In other words, how to obtain efficiently the highest possible electrical conductivity of the gas at temperatures which present-day containment materials can withstand (2000°–2500°K).

(3) How to extract the required high current densities from the electrode material at temperatures which would not cause high rates of evaporation of the electrode

* Recent discoveries by the Bell Telephone Laboratories of the niobium-310 super-conducting alloy brings this goal much closer to realization.

material, or conflict with the temperature which the flow-containment material can withstand.

The state of the art in regard to structural materials presents possible solutions in the refractory materials SiO_2, Al_2O_3, ZrO_2, HfO_2, and BN which have melting points of 1983°, 2353°, 2923°, 3053° and 3273°K, respectively, which have good oxidation resistance and good thermal-shock resistance, and which can be operated up to the temperature limits of 1673°, 2223°, 2573°, 2573° and 3053°K for BN (with perpendicular crystal orientation), respectively, without appreciable volatility of the material. These materials also mantain their thermal and electrical insulation resistance at fairly high operating temperatures. Graphite and some of the carbides, such as ZrC, TaC and HfC, (1) have higher melting points (>4073° (for graphite) and 3783°, 4133°, 4183°K for the three carbides, respectively), (2) high temperatures at which appreciable volatility begins to occur (2973° for graphite, 2513°, 4053° and 2513°K for the three carbides, respectively, under non-oxidizing atmospheres), and (3) good thermal-shock resistance. But they have extremely poor oxidation resistance and are electrically conducting or semi-conducting even at room temperature. Other interesting high-temperature ceramics are the mixed oxides, $CaZrO_3$, $SrZrO_3$ and $BaZrO_3$ with melting points of (2573°, 2973°, 2973°K, respectively) and excellent oxidation resistance: no data regarding their other pertinent properties are currently available.

So far, graphite and the carbides ZrC, TaC and HfC (although not suitable as containment materials) offer the best solution to the cathode material because of their good resistance to thermal shock and their good thermionic emission properties at temperatures comparable to the containment material temperatures without excessive evaporation. This solution is, however, limited to current densities below, or about one million amp/m^2 or 100 amp/cm^2.

However, in regard to the problem of electrical conductivity and ionization of the gas, the present state of the art in experimental research has followed one workable approach to the partial ionization of air or the low atomic number noble gases. This approach is known as "seeding" the gas; i.e., introducing into the hot stream a quantity of about 1–2 per cent of a more easily ionized vapor such as potassium or potassium carbonate which then evaporates and is thermally ionized by extracting sufficient amounts of energy from the main gas stream. In the MHD generator experiments made using this seeding approach, [2] the electrical conductivities achieved were, (1) 350 mho/m with air and carbon at a stagnation temperature of 5500°K; (2) 65 mho/m with argon at a stagnation temperature of 3260°K; and (3) 47·5 mho/m with flue gas at a stagnation temperature of 3030°K. These reported conductivity values when compared to those of copper used in most dynamo-electric machines are lower by a factor of 10^5–10^6. This would mean an internal volume of the MHD generator of 10^6 times that of a copper winding in an armature operating at a peripheral speed equal to the flow velocity. However, with the high flow velocities possible (1350, 688 and 820 m/sec in the above-mentioned experiments) this factor can be decreased to about 10^3–10^4.

During these experiments on MHD generators, the maximum power densities achieved were 63 MW/m^3 with air and carbon at an inlet stagnation temperature of 5500°K, and 20 MW/m^3 with argon at an inlet stagnation temperature of 3260°K and 3 MW/m^3 with flue gas at an inlet stagnation temperature of 3030°K. The open-circuit voltages obtained were 31, 55 and 43 V at velocities of 1350 m/sec, 688 m/sec and 820 m/sec, respectively, and at magnetic field intensities of 0·860 Wb/m^2, 1·4 Wb/m^2 and 1·4 Wb/m^2, respectively. The short-circuit currents were 150, 800 and 370 amps, respectively. The mass flow was

0·45 kg/sec, 0·3 kg/sec and 0·5 kg/sec, respectively, for channel dimensions of $1 \times 5 \times 5$ cm, $2{\cdot}5 \times 7{\cdot}5 \times 50$ cm and $4 \times 12 \times 40$ cm. The insulator materials used in the first and last generator were silica and zirconia, respectively. Graphite was used as the electrode materials in both experiments.

These experimental units could only be tested for durations of 9, 5, and 240 sec, respectively; the last for a longer time because of its relatively low power density and relatively low wall temperature of 2975°K, compared to the temperature of excessive volatility of zirconia of 2570°K.

Although the efficiencies measured during these experiments were very poor (below one per cent) they served to demonstrate the feasibility of an MHD generator having appreciable output power densities with present approaches to ionization and the use of existing materials.

5. CONCLUSIONS

With the results of these experiments before us, we realize that the feasibility in the near future of an MHD generator having the desirable power densities together with long durable life and using existing materials necessitates greater and continued research efforts to explore other approaches to the question of partial ionization of the gas which would lead to reasonable electrical conductivity of the gas (on the order of 500 mho/m) at reasonably low temperature (stagnation temperature of around 2000°K) and for appreciable dynamic flow conditions (inlet pressure 0·1 atm).

If we are to limit our ionization approach to the seeding technique, without the development of a new refractory insulation material capable of withstanding temperatures over 3000°K for a long period, then the MHD generator will be limited to applications where only large pulses of power of short duration are needed.

In conclusion, energy conversion by utilizing the MHD electric power generator concept appears to be best suited for generating power outputs in the multimegawatt range using heat sources such as the closed-cycle very-high-temperature nuclear reactor system, open-cycle rocket engine, and ultimately the energy released from a controlled thermonuclear fusion. The importance of these energy sources justifies the interest in research in the field of MHD energy conversion.

Overall conversion efficiencies in the range of 25 per cent seem realizable, but power densities of tens of MW/m^3 or tens of kW/kg are research goals which must await the realization of high electrical conductivity of the ionized gas or plasma at temperatures compatible with present-day structural or electrode materials, or the development of new materials in the future. The research field is open to new approaches to efficient ionization and to the current extraction problem.

Acknowledgement—The author would like to thank R. R. Stephenson for his very helpful comments on the manuscript and for programming the equations developed in this paper on the digital computer.

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EFFICIENCY OF A NUCLEAR-THERMIONIC GENERATOR

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INTRODUCTION

WORKING within the limits imposed by currently available materials and techniques, the cesium-filled thermionic generator driven by fission heating should be capable of producing electric power at a thermal efficiency in excess of 20 per cent. To demonstrate this point, the design criteria for a generator operating at an arbitrarily selected operating point are presented in this paper, along with a commentary on the validity of the assumptions used. The design calculation is necessarily idealized. However, at each stage it is possible to see how a required change in parameters would affect the predicted performance figures.

MATERIALS AND GENERAL CONFIGURATION

Figure 1 portrays in simplified form the generator configuration. The central cylinder is a uranium-bearing fuel element which also serves as the thermionic cathode and as a

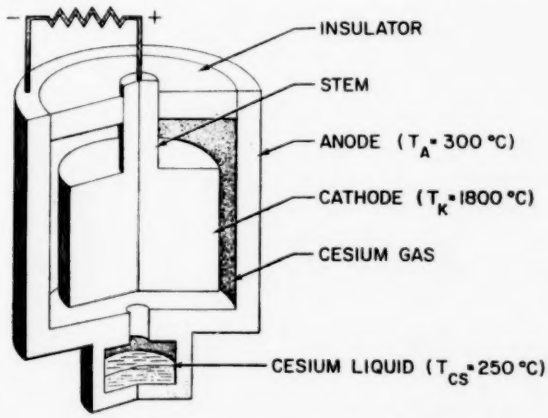

FIG. 1. Sketch of nuclear-thermionic generator.

conductor of the electric current. Surrounding the fuel element is a container which acts also as the anode. A gap of 1 mm or less separates the fuel element from the anode. Placed in a separate zone is a pool of cesium metal. An electrical insulator serves to complete the enclosure. Electric power is delivered to the load via connections to the cathode and anode, which are the poles of the generator.

No scale factor is given, other than the required cathode-anode spacing. In the calculations given below, performance is calculated on the basis of 1 cm^2 of fuel-element surface

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area. It is assumed that a sufficient number of modules, taken in aggregate, form a critical assembly. The fissioning process liberates sufficient heat to raise the fuel element surface temperature to 1800°C. A heat exchange system must be provided to cool the anode to 300°C. The cesium reservoir, which could be common to all modules, is maintained at 250°C.

Table 1 illustrates some of the essential attributes of the materials. The material selected for the cathode is a solid solution of uranium carbide in zirconium carbide. The solution contains a fissionable material and is a good electrical conductor. The melting point of UC is 2450°C and that of zirconium carbide is 3500°C. The value of the work function of the solution for thermionic emission is 3·3 V. The selection of nickel as the anode material is arbitrary, except that it is one of the good electrical conductors which can operate at intermediate temperature. The essential property of the anode is the thermionic work function, 1·8 V, which is determined by the coating of cesium on the surface which will be formed at the operating temperature selected. The work functions are the determinants of electrical performance.

TABLE 1. NECESSARY PROPERTIES OF CATHODE AND ANODE MATERIALS

	Cathode	Anode
Material	UC : ZC	Cs on Ni
Work function, (V)	3·3	1·8
Optical emissivity	0·5	0·2

Infrared radiation is the dominant form of thermal power loss. The amount of power radiated is controlled at the total optical emissivities of the two surfaces. Since the emissivity of the cathode is uncertain, the benefit derived from considering it is not used. The emissivity of the anode surface, 1/5, is used as the effective emissivity in the calculation. The measured emissivity of nickel at 300°C is about 1/10, but an allowance is made for the effects of cesium coating and of possible contaminants.

OPERATION OF THE CONVERTER

Figure 2 shows the electrostatic potential for an electron in the generator. At the left is a uniform level corresponding to the potential energy of the electron in the cathode conductor. To emerge from the cathode into the gap, the electron must overcome a high work function barrier, Φ_K. At the surface an electric emission current density of J_K amp/cm^2 is indicated. Also, it must be assumed that a material current, J_0, is produced by sublimation from the surface. The sublimation rate is the principal determinant of generator life.

If the gap were maintained in a vacuum, there would be a much higher potential barrier within it as a result of free-electron repulsion, and the maximum current would be limited, because of this effect alone, to the order of mamp/cm^2. However, the cesium vapor introduced into the gap is partially ionized, and the positive ion density in the gap neutralizes the electron space charge. As a consequence, the electrostatic potential formed in the gap is

shown, somewhat oversimplified, as a straight line connecting the potential levels at the cathode and anode surfaces.

When the electron leaves the gap region and enters the anode it must descend through a potential drop Φ_A, the anode work function. Whatever potential energy remains, the

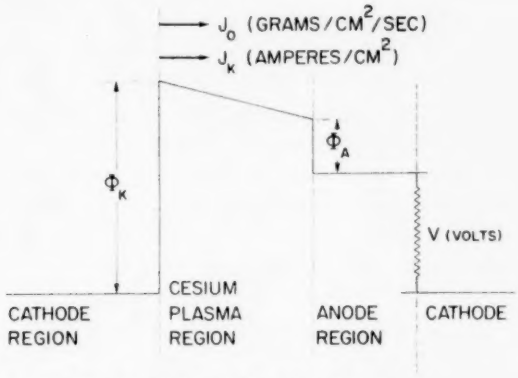

FIG. 2. Electrostatic potential diagram.

difference between the internal levels in the cathode and anode, can be impressed on the external load resistance. It is clear from this point that the energy loss corresponding to the potential drop Φ_A corresponds to the thermal exhaust. The loss should be minimized, obviously, but there is a very definite lower limit to the exhaust energy.

Using the electrostatic potential diagram, the electric output characteristic can be deduced. This characteristic is shown in Fig. 3. In a series of satellite figures, the forms of

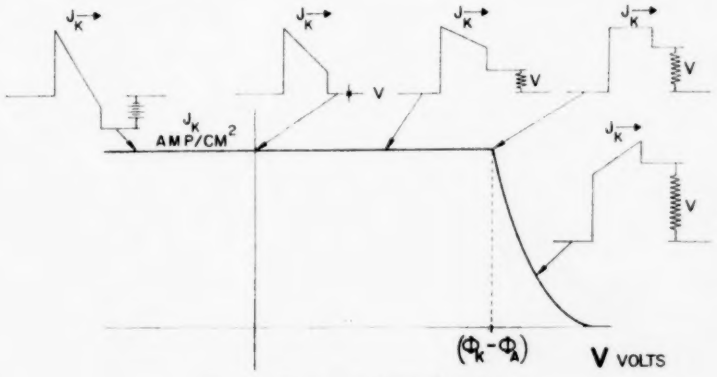

FIG. 3. Current–voltage diagram.

the potential diagram are shown at points corresponding to the specific output points. The variable in the system is the output voltage, V. In the power-generation cycle between short circuit ($V = 0$) and open circuit (current $= 0$) the voltage, V, can be adjusted simply by varying the value of the load resistance. Outside this range, to obtain either lesser or greater voltages, a battery must be impressed in the circuit.

In all cases where the voltage level at the anode surface is less than the voltage level at the cathode surfaces, the current is constant, independent of the output voltage. This is true because the highest barrier the electron must overcome is the cathode work function. Having traversed this barrier, the electron has only to travel downhill in potential. A unique point is reached when the anode and cathode surface potential levels are evenly matched. This is the point corresponding to the discontinuous break in the current voltage characteristic. As the voltage, V, and likewise the anode potential level, is raised still higher, the highest barrier to electron transit is posed by the anode, not the cathode. For this condition, the current decreases exponentially with increasing voltage.

It is evident almost by inspection that the maximum power point is at, or near, the break-point. Until this point is reached, an increase in load voltage is obtained with no reduction of load current. Beyond this point, increased load voltage is obtained only at the expense of a sharp decrease in load current. The output voltage at the break-point, or maximum power point, is seen, by identity, to be the difference in the two work functions, $\Phi_K - \Phi_A$.

CALCULATION OF EFFICIENCY

The electric performance data shown in Fig. 4 are calculated assuming operation at the maximum-power point. Given a cathode operating temperature of 1800°C and a work

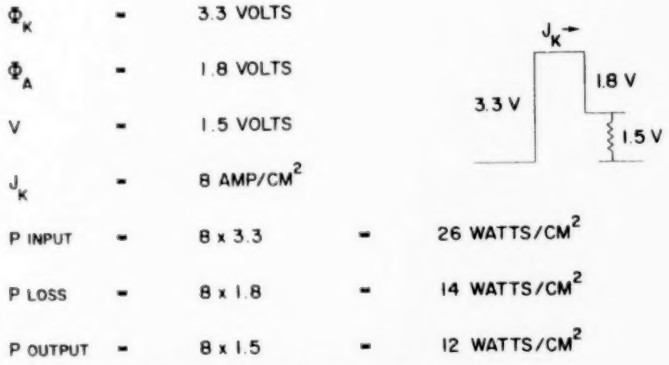
Φ_K = 3.3 VOLTS
Φ_A = 1.8 VOLTS
V = 1.5 VOLTS
J_K = 8 AMP/CM^2
P INPUT = 8 x 3.3 = 26 WATTS/CM^2
P LOSS = 8 x 1.8 = 14 WATTS/CM^2
P OUTPUT = 8 x 1.5 = 12 WATTS/CM^2
J_K
3.3 V
1.8 V
1.5 V

FIG. 4. Electric performance of the generator.

function of 3·3 V, the saturated emission current is 8 amp/cm^2. The output voltage is 3·3 V minus 1·8 V, or 1·5 V. The output power density is 12 W/cm^2. Also important to the efficiency calculation to follow is the total electric power input, which is the power required to drive the current over the cathode work function barrier. This is 26 W/cm^2, corresponding, in thermoelectric terminology, to the Peltier cooling at the surface of the heat source.

Table 2 lists the major forms of thermal loss. The dominant form of power loss is by radiation. Black-body emission at 1800°C (σT^4) is 100 W/cm^2. Using an effective emissivity of 1/5, that loss is reduced to 20 W/cm^2. Heat conduction through the plasma is estimated from data available for a rubidium gas; the figure is unreliable but sufficiently small that a possible error is not likely to affect the conclusions. It is taken to be 1·5 W/cm^2. Losses in the stem supporting member for the fuel element are unavoidable, due to the physical relationship between thermal and electrical conductivities in metals. When the stem shape is optimized for conduction and joule-heating losses, the net loss is usually about 10 per

cent of the net output power. The loss is therefore quoted here per unit area of operating cathode surface area.

TABLE 2. THERMAL LOSSES IN THE SYSTEM

Source	Loss (W/cm^2)
Cathode radiation	20·0
Plasma conduction	1·5
Stem (conduction and joule)	1·2
Total	23·0

The data concerning the electrical performance and the thermal losses may be combined to yield a predicted efficiency. The total power input is 49 W/cm^2, consisting of 26 W/cm^2 electrical input and 23 W/cm^2 of thermal losses. The output power density is 12 W/cm^2 of cathode surface area, resulting in an efficiency of 12/49, or about 24 per cent.

DISCUSSION

Although the performance of the system could be improved, such improvements must await advances in the performance of available materials. Even in the example described, current materials are being pressed to their limits. A notable improvement would be obtained by lowering the anode work function. Improvement here is possible, but there is a limit to the net gain to be expected. One of the implicit assumptions in the calculations has been that the current is emitted only by the cathode. When the anode work function is reduced nearly zero, this assumption is invalid, for even at the low anode temperature assumed, some emission will take place. The anode work function is, by mechanical analog, a valve which prevents the machine from running in reverse; it is the mechanism which prevents the generator from operating in excess of the Carnot thermodynamic limit to efficiency. The limit for the present example is readily found by postulating that the anode current (or back current) should not exceed 10 per cent of the forward current. This condition would be met if the anode, held at 300°C, had a work function of 1·0 V. The rest of the parameters being held constant, the output voltage would then rise to 2·3 V and the corresponding output power would be nearly 18 W/cm^2. Research in the field is naturally being directed toward obtaining a stable, reliable anode with a work function of 1·0 V.

It is interesting to note that if the 1·8-V anode work function is retained, then the anode temperature can be raised significantly before performance is impaired due to back-emission. The back-emission would reach 0·8 amp/cm^2 (10 per cent of the forward current) only when the anode temperature is increased to 900°C. It is this fact which has caused the interest in the thermionic generator for space power, since the high temperature for heat radiation permits the use of a small, low-weight radiator for power exhaust.

The use of the ideal output characteristic as a basis for performance calculations should be questioned. In cells currently operating, the output characteristics agree excellently with the thermionic-electrostatic model presented when current densities are below 3 amp/cm^2. At higher levels, the effect of the resistance of the cesium plasma is observed, with a consequent lowering of the output current below the saturated emission current. In extension, experiments have shown that the plasma resistance effect can be reduced by decreasing

the spacing below 1 mm. The effects of spacing are still being investigated and it is reasonable to expect the spacing-resistance question to be resolved in the near future.

The critical question is reserved to the end, so that the appropriate course for further investigation can be identified. This is the materials question. First, it can be asked whether the choice of 1800°C cathode operating temperature is on a firm footing. It is, because of the nature of the thermionic emission laws. At 1700°C the maximum current approaches 2 amp/cm^2, certainly a lower limit for useful output power densities in comparison with the thermal losses. At the other extreme, the current at 1900°C would be about 30 amp/cm^2. Using present techniques this is an extreme upper limit to the current density that can suitably be space-charge neutralized. Also, the electric conduction losses within the fuel elements become severe at this level of current. Thus, the practical range for cathode operating temperature is quite narrowly centered about the 1800°C point selected.

Available metallurgical data related to vaporization loss would restrict the operating lifetime at 1800°C to about 1000 hr. In 1000 hr the loss of fuel would be about 10 mg/cm^2 of surface area. This figure represents an extreme value from the standpoint of practical reactor design, since it represents free evaporation into a perfect vacuum and the cesium-filled gap is not a perfect vacuum. Also, the evaporation is not free, in that evaporated fuel must be supplied to the surface by diffusion within the fuel body. Additionally, it is not excluded that further stabilization of the polycarbide element can be achieved.

In final summary, the 1000 hr life that can be achieved today is not suitable for reactor design. The key to a program leading to a successful reactor experiment lies in an extension of the high-temperature metallurgical research currently underway.

SESSION II

PHYSICAL THEORY

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GENERALIZED CALCULATION OF THERMOELECTRIC EFFICIENCY

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INTRODUCTION

THERE exist several methods for calculating the efficiency of thermoelectric generators. In the well-known method of Telkes [1], Joffé [2] and others it is assumed that the Seebeck coefficient S, electric conductivity σ and thermal conductivity κ are constant with respect to temperature and the average values of these quantities are then used in the final results. In general this method is inaccurate. An exact calculation of thermoelectric efficiency has been carried out by Sherman, Heikes and Ure [3] by means of high speed computer techniques. Their method requires that numerical values of S, σ and κ be known throughout the temperature range of interest. Each of these quantities depends upon the doping of the thermocouple materials. Thus the problem of optimizing the doping would involve some sort of iterative procedure. Finally, the infinite-staging approach of Zener [4] provides an exact upper bound to the thermoelectric efficiency [3] yet the optimization problem is considerably less difficult than in the preceding method.

In this paper the infinite staging method is used to derive a set of "universal curves" from which one may obtain the maximum efficiency η_m for any thermocouple whose branches are extrinsic semiconductors of the same base material. The parameters of the study involve only the following fundamental physical properties of semiconductors: electron and hole conductivity mobilities μ_n and μ_p, density-of-states effective masses m_n^* and m_p^*, lattice thermal conductivity κ_L, reduced energy gap ξ_g $(=E_g/kT)$ and the scattering indices s_n and s_p.

A required minimum value of ξ_g is also defined by a set of "universal curves". These curves enable one to determine the temperature at which the onset of mixed conduction occurs.

The three distinct cases of interest are as follows:

1. If the semiconductor remains extrinsic throughout the entire temperature range then η_m depends only upon the scattering indices and the local values of the dimensionless "material parameter", given by

$$\beta = \text{const.} \times \frac{(\mu_n \mu_p)^{1/2}}{\kappa_L} \left(\frac{m_n^* m_p^*}{m^2}\right)^{3/4} T^{5/2} \tag{1}$$

   where m is the mass of a free electron and T is the absolute temperature.
2. If mixed conduction occurs then η_m depends in a complicated fashion upon s_n, s_p and the local values of both β and ξ_g.
3. For the hypothetical case in which κ_L is negligibly small η_m depends only upon s_n, s_p and the local values of ξ_g.

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THERMOELECTRIC EFFICIENCY

The over-all efficiency of N thermoelectric stages in thermal cascade is given by

$$\eta = 1 - (1 - \eta_1)(1 - \eta_2) \ldots (1 - \eta_N) \tag{2}$$

where η_i is the efficiency of the i-th stage. If the temperature difference across each stage is sufficiently small then

$$\eta_i = \epsilon(T_i)\, \Delta T_i / T_i \tag{3}$$

where

$$\epsilon(T) = \frac{(1 + ZT)^{1/2} - 1}{(1 + ZT)^{1/2} + 1} \tag{4}$$

and where Z is the "figure of merit" given by

$$Z = \left[\frac{S_p - S_n}{(\kappa_n/\sigma_n)^{1/2} + (\kappa_p/\sigma_p)^{1/2}}\right]^2 \tag{5}$$

If one takes the limit as $N \to \infty$, keeping fixed the temperatures of the hot and cold junctions then

$$\eta^{\infty} = 1 - \exp\left[-\int_{T_0}^{T_1} \frac{\epsilon(T)}{T}\, dT\right] \tag{6}$$

where T_1 and T_0 are the temperatures of the hot and cold junctions respectively. It may be shown that the efficiency is always increased by breaking up the temperature difference into two stages [3]. Thus equation (6) gives an exact upper bound on the thermoelectric efficiency. It has been found that η^{∞} may be closely approximated by a small finite number of stages.

THERMOELECTRIC COEFFICIENTS

It is first necessary to assume that the mean free paths of electrons and holes have an energy dependence of the form

$$l(E, T) = l_0(T)\, (E/kT)^s \tag{7}$$

where E is the energy, k is the Boltzmann constant and s is a constant scattering index. Then

$$\mu = \mu_0\, T^r \tag{8}$$

where μ_0 is the mobility extrapolated to $T = 0°K$. Table 1 gives the theoretical values of s and r for various scattering mechanisms. In the case of mixed scattering a relation of the form of equation (7) is often used as an approximation.

TABLE 1. THEORETICAL VALUES OF s AND r FOR VARIOUS SCATTERING MECHANISMS

Scattering mechanism	s	r
Impurity ions	2	3/2
Ionic lattices at high temperatures	1	−1/2
Atomic lattices (classical semiconductors)	0	−3/2
Constant frequency vibrations	−1	−5/2

According to semiconductor theory [5, 6], the thermoelectric coefficients for an extrinsic semiconductor are given by

$$|S| = (k/e)(A - \xi) \tag{9}$$

$$\sigma = Ce\mu f(\xi) \tag{10}$$

$$\kappa = \kappa_L + L(k/e)^2 \sigma T \tag{11}$$

where

e = electronic charge

ξ = reduced Fermi level (E_F/kT)

$C = 2(2\pi m^* kT/h^2)^{3/2}$

= effective density of states

h = Planck constant

The dimensionless quantities f, A, and L are given in Table 2 as functions of the Fermi integrals

$$F_s(\xi) = \int_0^\infty \frac{x^s \, dx}{\exp(x - \xi) + 1} \tag{12}$$

TABLE 2. DIMENSIONLESS THERMOELECTRIC PARAMETERS IN TERMS OF FERMI INTEGRALS

	$s = -1$	$s > 0$
f	$\dfrac{2/\pi^{1/2}}{\exp(-\xi) + 1}$	$F_s(\xi)/s!$
A	$[\exp(-\xi) + 1] F_0(\xi)$	$\dfrac{s+2}{s+1} \dfrac{F_{s+1}(\xi)}{F_s(\xi)}$
L	$2[\exp(-\xi) + 1] F_1(\xi) - A^2$	$\dfrac{s+3}{s+1} \dfrac{F_{s+2}(\xi)}{F_s(\xi)} - A^2$

The classical approximation ($\xi < -1$) gives

$$f(\xi) = \exp(\xi) \tag{13}$$

$$A = L = s + 2 \tag{14}$$

EXTRINSIC SEMICONDUCTORS

The figure of merit for an extrinsic semiconductor is

$$Z = S^2\sigma/\kappa = T^{-1}(A - \xi)^2/(L + \lambda) \tag{15}$$

where

$$\lambda = [\beta f(\xi)]^{-1} \tag{16}$$

and

$$\beta = C\mu k^2 T/e\kappa_L$$

$$= 8{\cdot}952 \times 10^{-6} (\mu/\kappa_L)(m^*/m)^{3/2}(T/300)^{5/2} \tag{17}$$

Chasmar and Stratton [7], using Fermi-Dirac statistics, have determined graphically the maximum of Z with respect to ξ for various values of β and s.

On the basis of classical statistics the maximum figure of merit is given by [7]

$$\begin{aligned} Z_m T &= \xi_0'(\xi_0' - 2)/L \\ &= 4\beta \exp(\xi_0' + s)\,[1 + L\beta \exp(\xi_0' + s)] \end{aligned} \tag{18}$$

where the optimum Fermi level is defined by the transcendental equation

$$-\xi_0' \exp(-\xi_0' - s) = 2L\beta \tag{19}$$

and

$$\xi' = \xi - A + 2 = \xi - s \tag{20}$$

In Fig. 1 the exact values of $Z_m T$ as a function of β are compared with the values obtained from the classical approximation. For the range $-1 \leq s \leq 0$, which includes virtually all

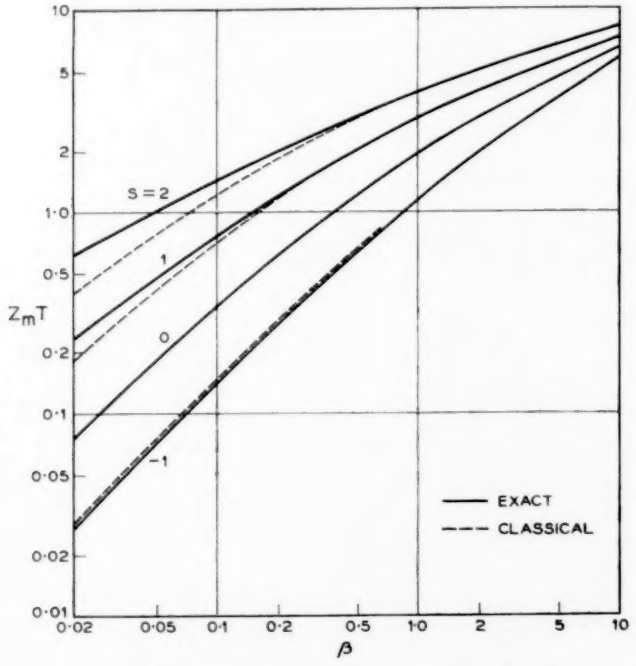

FIG. 1. Variation of the maximum figure of merit with material parameter and scattering index.

the present thermoelectric materials, these values agree to within 5 per cent. This agreement is fortuitous since the classical approximation tends to underestimate S while it overestimates σ. As shown in Fig. 2 the classical approximation for ξ_0 is in considerable error for small values of β. However, the classical values of Z_m and ξ_0 are exact for $\beta \gg 1$.

In general the conditions which maximize the figure of merit of a thermocouple differ from those which maximize the figures of merit of the branches taken individually. To obtain these conditions the classical approximation may be used without incurring serious error except for $s > 0$ and $\beta \ll 1$.

Stratton [8] has purported to show how the thermocouple may be replaced by a hypothetical single material having certain "average" parameters. However, he employs the erroneous assumption that

$$L\beta \exp(\xi_0) \gg 1$$

This condition cannot in fact be satisfied since ξ_0 becomes increasingly negative as β increases and the left-hand side of the inequality has an upper bound of the order of unity.

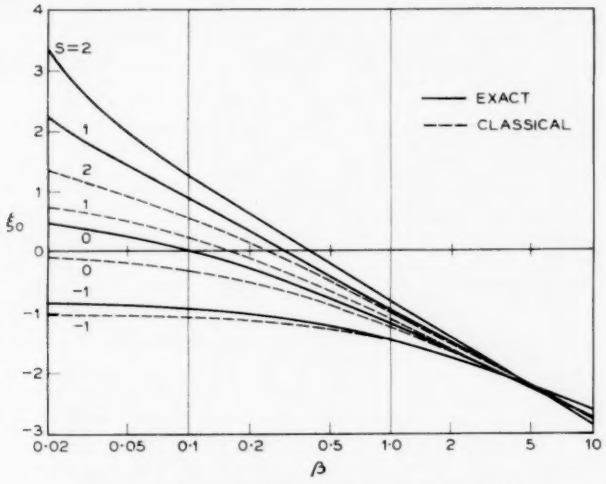

FIG. 2. Variation of the optimum Fermi level with material parameter and scattering index.

The figure of merit for a thermocouple whose branches are extrinsic semiconductors is given by

$$ZT = \left[\frac{A_n - \xi_n + A_p - \xi_p}{(L_n + \lambda_n)^{1/2} + (L_p + \lambda_p)^{1/2}}\right]^2 \tag{21}$$

If

$$| L_p - L_n | \ll \min (L_p, L_n)$$

then, as shown in the appendix

$$\begin{aligned} Z_m T &= (\xi'_{n0}/a_n)\,(\xi'_{n0}/a_n - 2)/L_n \\ &= 4\beta \exp(\xi'_{n0} + s)\,[1 + L_n\,\beta \exp(\xi'_{n0} + s)] \end{aligned} \tag{22}$$

where

$$\beta = (\beta_n\,\beta_p)^{1/2}, \qquad s = \tfrac{1}{2}(s_n + s_p) \tag{23}$$

and

$$a_n = (3L_n + L_p)/4L_n, \qquad a_p = (L_n + 3L_p)/4L_p \tag{24}$$

The optimum Fermi levels are defined by

$$-\xi'_{n0} \exp(-\xi'_{n0} - s) = 2a_n\,L_n\,\beta \tag{25}$$

and

$$-\xi'_{p0} \exp(-\xi'_{p0} - s) = 2a_p\,L_p\,\beta \tag{26}$$

where

$$\xi'_n = \xi_n - s - \tfrac{1}{2}\ln(\beta_p/\beta_n) \tag{27}$$

and

$$\xi_p' = \xi_p - s - \tfrac{1}{2}\ln(\beta_n/\beta_p) \tag{28}$$

It may be observed that Z_mT depends upon temperature only through the material parameter.

$$\beta = 8{\cdot}952 \times 10^{-6}\,\frac{(\mu_n\,\mu_p)^{1/2}}{\kappa_L}\left(\frac{m_n^*\,m_p^*}{m^2}\right)^{3/4}\left(\frac{T}{300}\right)^{5/2} \tag{29}$$

κ_L varies inversely with temperature for pure semiconductors; it is essentially independent of temperature for many alloys [9]. The mobilities vary as T^r, where the values of r for various scattering mechanisms are given in Table 1. Thus the material parameter has a temperature dependence given by

$$\beta = \beta_0(T/T_0)^p \tag{30}$$

where

$$p = \tfrac{1}{2}(5 + r_n + r_p) + 1 \quad \text{for pure semiconductors} \tag{31}$$

and

$$p = \tfrac{1}{2}(5 + r_n + r_p) \quad \text{for alloys} \tag{32}$$

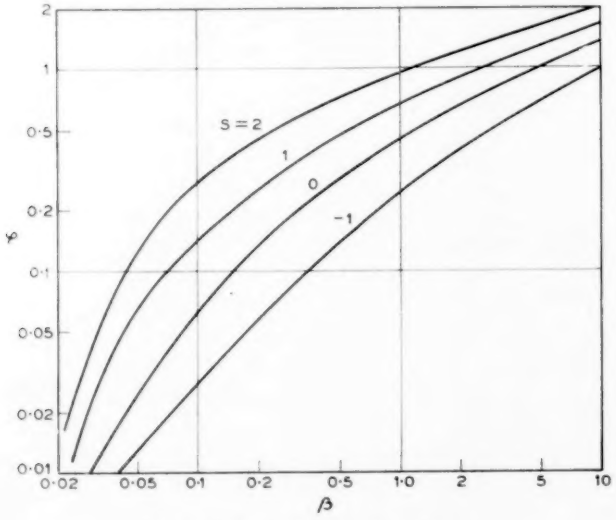

FIG. 3. Universal efficiency curves.

Letting $Z_mT = F(\beta)$, equation (6) may be written in the form

$$\eta_m = 1 - \exp[-\phi(\beta, \beta_0)/p] \tag{33}$$

where

$$\phi(\beta, \beta_0) = \int_{\beta_0}^{\beta} \frac{[1 + F(\beta)]^{1/2} - 1}{[1 + F(\beta)]^{1/2} + 1}\,\frac{\mathrm{d}\beta}{\beta} \tag{34}$$

For the case of equal scattering indices ($s_n = s_p = s$), $\phi(\beta, 0{\cdot}02)$ has been integrated graphically for $0{\cdot}02 < \beta < 10$ with s as parameter. Figure 3 exhibits the variation of ϕ with β. The choice of β_0 is unimportant since

$$\phi(\beta_2, \beta_1) = \phi(\beta_2, \beta_0) - \phi(\beta_1, \beta_0) \tag{35}$$

The efficiency is obtained simply by substituting in equation (33) the value of ϕ obtained from Fig. 3.

For the special case $p = 0$, Z_mT is independent of temperature so that

$$\eta_m = 1 - (T_0/T_1)^{\epsilon} \tag{36}$$

where ϵ is defined by equation (4).

If β is sufficiently small then $\xi'_{n0} \approx \xi'_{p0} \approx 0$ and

$$Z_mT \approx 4\beta \exp(s) \tag{37}$$

where

$$\beta = (\beta_n \beta_p)^{1/2}, \qquad s = \tfrac{1}{2}(s_n + s_p) \tag{23}$$

Let

$$u(T) = [1 + 4\beta(T) \exp(s)]^{1/2} \tag{38}$$

Then

$$\phi(u) = \int_{u_0}^{u} \frac{u \, du}{(u+1)^2}$$

$$= 2\left[\ln\left(\frac{u+1}{u_0+1}\right) + \frac{1}{u+1} - \frac{1}{u_0+1}\right] \tag{39}$$

and

$$\eta_m = 1 - \left(\frac{u_0+1}{u_1+1}\right)^{2/p} \exp\left[\frac{2}{p}\left(\frac{1}{u_0+1} - \frac{1}{u_1+1}\right)\right] \tag{40}$$

where

$$u_0 = u(T_0), \qquad u_1 = u(T_1).$$

AMBIPOLAR DIFFUSION

At high temperatures the onset of mixed conduction causes an increase in the thermal conductivity and a corresponding decrease in the Seebeck coefficient, thereby reducing the figure of merit. Neglecting any transport of thermal energy by excitons, the contributions to κ at high temperatures are given by [10]

$$\kappa = \underbrace{\kappa_L}_{\text{LATTICE}} + (k/e)^2 \, T[\underbrace{\sigma_n \, L_n}_{\text{ELECTRONS}} + \underbrace{\sigma_p \, L_p}_{\text{HOLES}} + \underbrace{(\sigma_n \, \sigma_p/\sigma) \, (L_n + L_p + \xi_g)^2}_{\text{AMBIPOLAR DIFFUSION}}] \tag{41}$$

where

$$\sigma = \sigma_n + \sigma_p$$
$$= e[C_n \, \mu_n \exp(\xi_n) + C_p \, \mu_p \exp(-\xi_n - \xi_g)] \tag{42}$$

If the concentration of minority carriers is small enough that $\sigma_p \ll \sigma_n$ for n-type material, or $\sigma_n \ll \sigma_p$ for p-type material then

$$\kappa_n = \kappa_L + (k/e)^2 \, \sigma_n T[L_n + (\beta_p/\beta_n) \, E(\xi_g) \exp(-2\xi_n)] \tag{43}$$

and

$$\kappa_p = \kappa_L + (k/e)^2 \, \sigma_p T[L_p + (\beta_n/\beta_p) \, E(\xi_g) \exp(-2\xi_p)] \tag{44}$$

where

$$E(\xi_g) = (L_n + L_p + \xi_g)^2 \exp(-\xi_g) \tag{45}$$

Similarly the Seebeck coefficients at high temperatures are given by

$$s_n = -(k/e)\,[A_n - \xi_n - (\beta_p/\beta_n)\,B_n(\xi_g)\exp(-2\xi_n)] \tag{46}$$

and

$$s_p = (k/e)\,[A_p - \xi_p - (\beta_n/\beta_p)\,B_p(\xi_g)\exp(-2\xi_p)] \tag{47}$$

where

$$B_i(\xi_g) = (A_i + \xi_g)\exp(-\xi_g), \qquad i = n, p \tag{48}$$

CRITICAL TEMPERATURES

The most important effect at high temperatures is the rapid increase in thermal conductivity due to ambipolar diffusion. Neglecting the corresponding decrease in the Seebeck coefficient, the figure of merit is given by

$$ZT = \left[\frac{(A_n - \xi_n) + (A_p - \xi_p)}{(L_n + \lambda_n + \beta^2 E\,\lambda_n^2)^{1/2} + (L_p + \lambda_p + \beta^2 E\,\lambda_p^2)^{1/2}}\right]^2 \tag{49}$$

If

$$|L_p - L_n| \ll \min(L_p, L_n)$$

then it may be shown that

$$Z_m T \approx \frac{Z_m^* T}{1 + 4\beta^2 E/Z_m^* T} \tag{50}$$

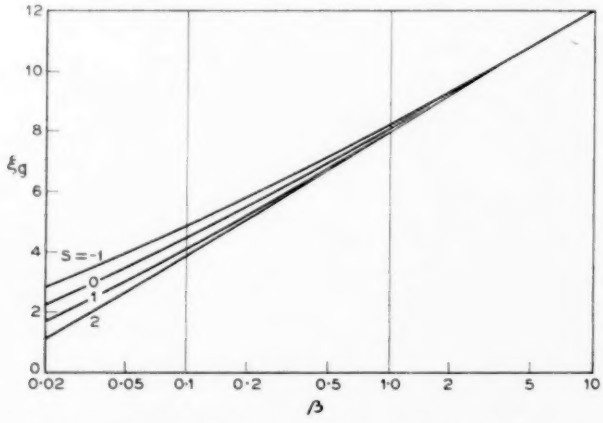

FIG. 4. Universal curves for the determination of critical temperatures.

where Z_m^* would be the maximum figure of merit if both thermocouple branches were extrinsic, as given by equation (22). Thus the critical temperature is determined by the condition

$$(L_n + L_p + \xi_g)^2 \exp(-\xi_g) \ll Z_m^* T/4\beta^2 \tag{51}$$

The minimum value of ξ_g required to satisfy the inequality

$$E(\xi_g) \leq 0{\cdot}1\, Z_m^* T/4\beta^2$$

is given in Fig. 4 as a universal function of β for various scattering indices, again assuming $s_n = s_p = s$. Since β and ξ_g are assumed known as functions of temperature, the critical temperature is thereby determined.

The critical temperature obtained from Fig. 4 is merely an estimate of the temperature

at which Z_mT is a maximum. The hot junction temperature may be considerably higher, as will be shown.

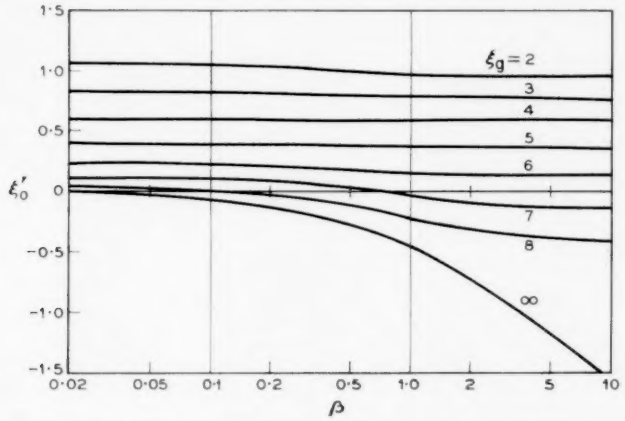

FIG. 5. Variation of the optimum Fermi level with material parameter and energy gap for $s = -1$.

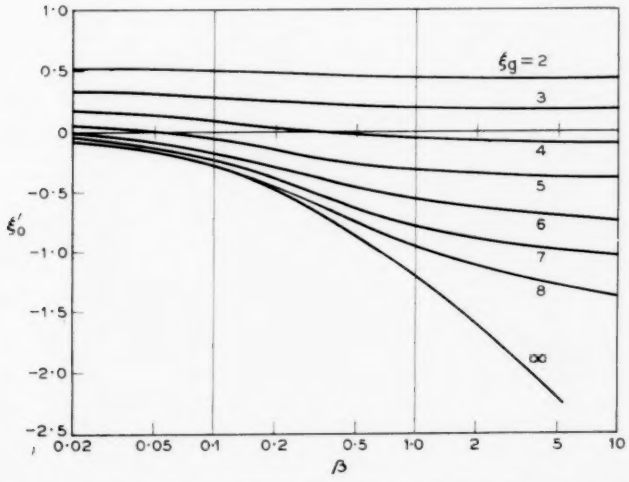

FIG. 6. Variation of the optimum Fermi level with material parameter and energy gap for $s = 0$.

MIXED CONDUCTION RANGE

For a thermocouple whose branches have equal scattering indices, the maximum figure of merit in the mixed conduction range is given by

$$Z_mT = \frac{[2 - \xi_0' - B\exp(-2\xi_0' - 2s)]^2}{L + \exp(-\xi_0' - s)/\beta + E\exp(-2\xi_0' - 2s)} \tag{52}$$

where ξ_0' satisfies the transcendental equation

$$2\beta = \frac{\exp(-\xi_0' - s)\,[-\xi_0' + 3B\exp(-2\xi_0' - 2s)]}{L - [(1 - \xi_0')\,E + 2LB]\exp(-2\xi_0' - 2s)} \tag{53}$$

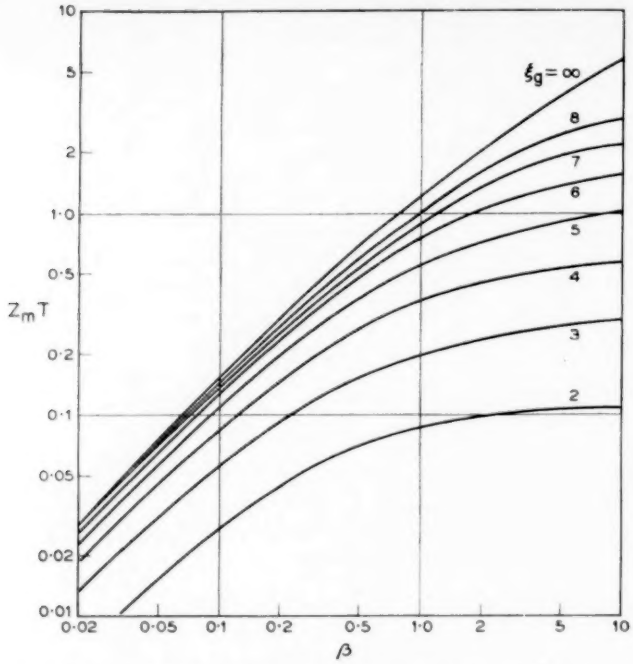

FIG. 7. Variation of the maximum figure of merit with material parameter and energy gap for $s = -1$.

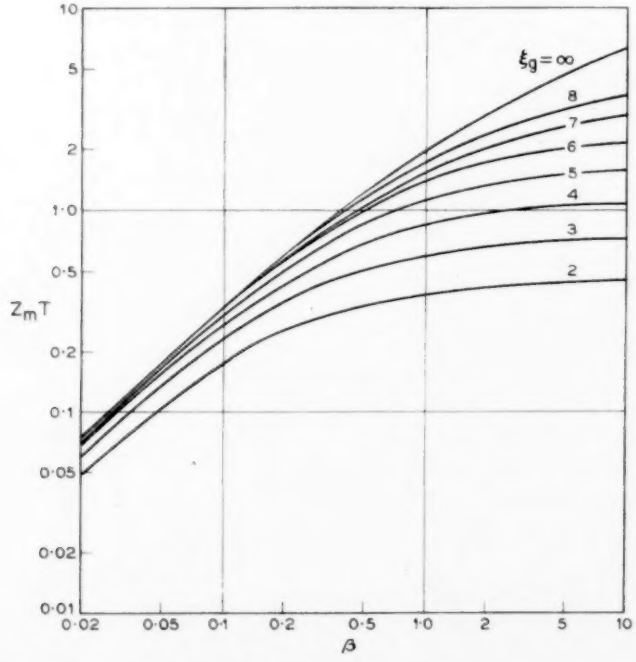

FIG. 8. Variation of the maximum figure of merit with material parameter and energy gap for $s = 0$.

Figures 5 and 6 exhibit ξ_0' as a function of β with ξ_g as parameter for $s = -1$ and $s = 0$, respectively. Figures 7 and 8 show the corresponding variation of Z_mT with β and ξ_g.

WFL SEMICONDUCTORS

Finally we may consider the hypothetical case in which κ_L is small enough that the Wiedemann–Franz–Lorentz (WFL) relation applies:

$$\kappa/\sigma = L(k/e)^2 T \tag{54}$$

Figure 9 is a reproduction of Price's theoretical "doping curve" [11] which exhibits the relationship between the Seebeck coefficient and the Fermi level. The optimum of ξ is that

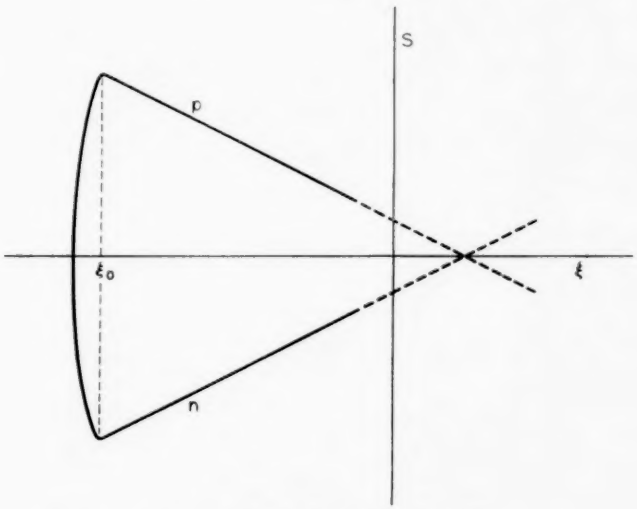

FIG. 9. Thermoelectric doping curve.

value which maximizes S. For a thermocouple whose branches consist of the same base material, the maximum value of S is

$$S_{pn} = (k/e)\,[\{\gamma(\gamma-2)\}^{1/2} - \ln\{\gamma - 1 + [\gamma(\gamma-2)]^{1/2}\}] \tag{55}$$

where

$$\gamma = \xi_g + A_n + A_p \tag{56}$$

Thus,

$$Z_mT = \left[\frac{\{\gamma(\gamma-2)\}^{1/2} - \ln\{\gamma - 1 + [\gamma(\gamma-2)]^{1/2}\}}{L_n^{1/2} + L_p^{1/2}}\right]^2 \tag{57}$$

In this case Z_mT depends upon temperature only through the dimensionless parameter

$$\gamma(T) = E_{g0}/kT + \lambda \tag{58}$$

where E_{g0} is the energy gap extrapolated to $T = 0$ and

$$\lambda = k^{-1}\,dE_g/dT + A_n + A_p \tag{59}$$

where dE_g/dT is assumed constant. Letting $Z_mT = G(\gamma)$, equation (6) may be written as

$$\eta_m = 1 - \exp[-\psi(\gamma, \gamma_0)] \tag{60}$$

where

$$\psi(\gamma, \gamma_0) = \int_{\gamma}^{\gamma_0} \frac{[1 + G(\gamma)]^{1/2} - 1}{[1 + G(\gamma)]^{1/2} + 1} \frac{d\gamma}{\gamma - \lambda} \tag{61}$$

and $\gamma_0 = \gamma(T_0)$. Thus the efficiency of a thermocouple whose branches are WFL semiconductors may be obtained from a set of universal curves which depend upon the scattering indices and the parameters γ and λ.

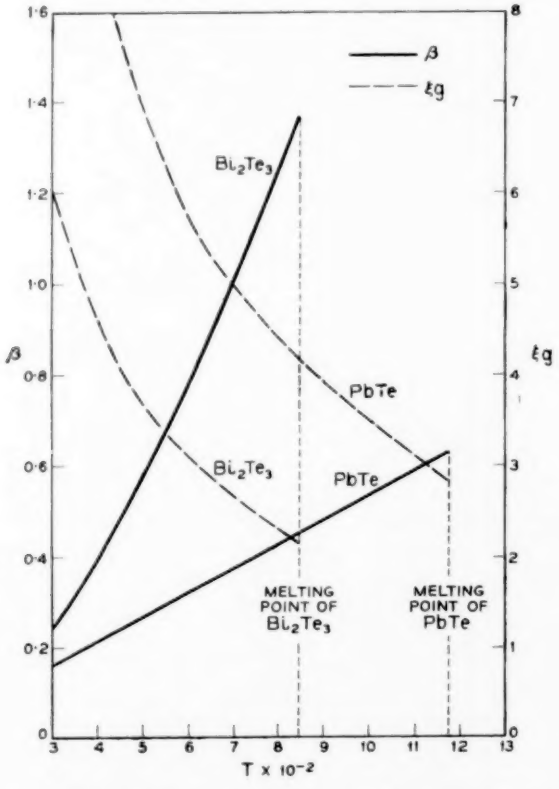

FIG. 10. Variation of material parameter and reduced energy gap with temperature for Bi_2Te_3 and PbTe.

APPLICATIONS

The results obtained above are now used to determine the performance of specific thermoelectric materials. Table 3 lists the electrical and thermal properties of Bi_2Te_3 [12] and PbTe [9,13]. The mobilities are given in $cm^2\ V^{-1}\ sec^{-1}$, the thermal conductivities in W $cm^{-1}\ deg^{-1}$, the energy gaps in eV and the melting points in °K. The other quantities are dimensionless.

TABLE 3. ELECTRICAL AND THERMAL PROPERTIES OF Bi_2Te_3 AND PbTe AT 300°K

	Bi_2Te_3	PbTe
s_n	−0·22	−1
s_p	−0·44	−1
μ_n	*	1620
μ_p	*	750
m_n^*/m	*	†
m_p^*/m	*	†
κ_L	0·0157	0·0215
β	0·242	0·161
E_g	∼ 0·16	∼0·30
Melting pt	846	1190

* Goldsmid [12] finds the values $\mu_n (m_n^*/m)^{3/2} = 430$ cm²V⁻¹ sec⁻¹ and $\mu_p (m_p^*/m)^{3/2} = 420$ cm²V⁻¹ sec⁻¹.

† It is assumed that $(m_n^* m_p^*)^{1/2}/m \approx 0{\cdot}5$.

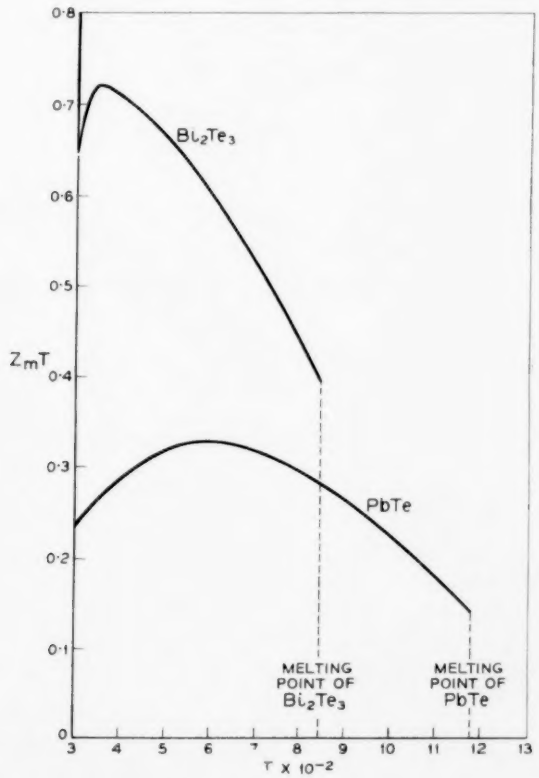

FIG. 11. Variation of the maximum figure of merit with temperature for Bi_2Te_3 and PbTe.

Due to the anisotropy of these materials unambiguous measurements of the effective masses have not been obtained [14]. There is also some uncertainty regarding the width of

the energy gap in PbTe. The value quoted above has been obtained from optical absorption data [13].

The approximate temperature dependences of β and ξ_g, assuming E_g constant, for Bi_2Te_3 and PbTe are shown in Fig. 10. It is possible then to calculate Z_mT as a function of temperature using Figs. 7 and 8 for PbTe and Bi_2Te_3 respectively. Figure 11 exhibits the variation of Z_mT with temperature up to the melting point of each material.

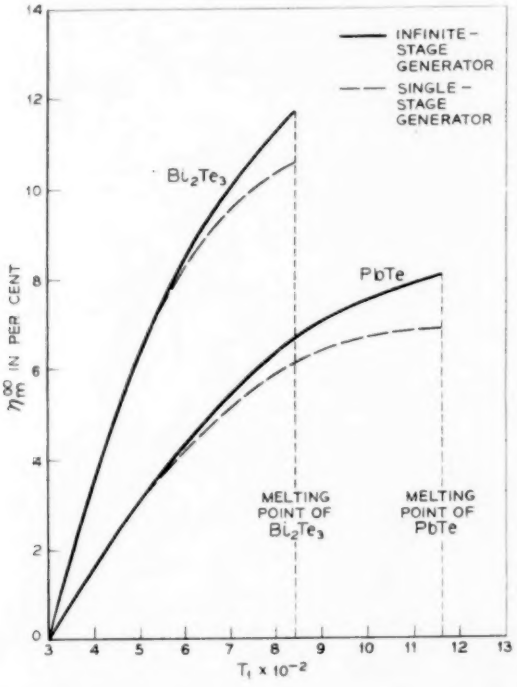

FIG. 12. Variation of efficiency with hot junction temperature for Bi_2Te_3 and PbTe, assuming $T_0 = 300$°K.

Assuming 300°K as the cold junction temperature, the infinite-stage efficiency has been calculated as a function of hot junction temperature by substituting in equation (6) the values of Z_mT obtained from Fig. 11 and integrating graphically. As shown in Fig. 12 the efficiencies of Bi_2Te_3 and PbTe continue to increase with increasing temperature up to their respective melting points. These are compared with the single-stage efficiencies computed from the approximate formula,

$$\eta = \frac{T_1 - T_0}{T_1} \frac{(1 + \overline{ZT})^{1/2} - 1}{(1 + \overline{ZT})^{1/2} + T_0/T_1} \tag{62}$$

where $\overline{ZT}$ denotes the average value with respect to temperature. It may be observed that the efficiency of an infinite-stage generator is closely approximated by that of a single-stage device except for large temperature differences between the hot and cold junctions.

APPENDIX

Maximum thermocouple figure of merit

On the basis of classical statistics the figure of merit for a thermocouple is

$$ZT = \left[\frac{A_n - \xi_n + A_p - \xi_p}{(L_n + \lambda_n)^{1/2} + (L_p + \lambda_p)^{1/2}}\right]^2 \tag{A1}$$

where

$$\lambda_i = \exp(-\xi_i)/\beta_i, \qquad i = n, p \tag{A2}$$

Setting $\partial Z/\partial \xi_i = 0$ gives the following conditions for maximum Z:

$$(L_n + \lambda_n)(1 + X) = \tfrac{1}{2}\lambda_n(A_n - \xi_n + A_p - \xi_p) \tag{A3}$$

$$(L_p + \lambda_p)(1 + X^{-1}) = \tfrac{1}{2}\lambda_p(A_n - \xi_n + A_p - \xi_p) \tag{A4}$$

where

$$X = \frac{\lambda_p}{\lambda_n} = \left(\frac{L_p + \lambda_p}{L_n + \lambda_n}\right)^{1/2} \tag{A5}$$

Thus,

$$\xi_n - \xi_p = \ln(X\beta_p/\beta_n) \tag{A6}$$

It may be shown that

$$X = \frac{\lambda_n + [\lambda_n^2 + 4L_p(L_n + \lambda_n)]^{1/2}}{2(L_n + \lambda_n)} \tag{A7}$$

If

$$|L_p - L_n| \ll L_n$$

then

$$X = \frac{\lambda_n + 2(L_n + \lambda_n)\left[1 + \dfrac{4\Delta L_n(L_n + \lambda_n)}{(2L_n + \lambda_n)^2}\right]^{1/2}}{2(L_n + \lambda_n)} \tag{A8}$$

$$\approx 1 + \Delta L_n/(2L_n + \lambda_n) = 1 + \delta$$

where

$$\Delta = (L_p - L_n)/L_n \tag{A9}$$

Thus

$$\ln X = \ln(1 + \delta) \approx \delta \tag{A10}$$

Combining (A3), (A6), (A8) and (A10) gives

$$(L_n + \lambda_n)(2 + \delta) = \tfrac{1}{2}\lambda_n[A_n + A_p - 2\xi_{n0} + \delta + \ln(\beta_p/\beta_n)] \tag{A11}$$

or

$$2L_n + \tfrac{1}{2}\delta(2L_n + \lambda_n) = -\lambda_n \xi_{n0}' \tag{A12}$$

where

$$\xi_n' = \xi_n - \tfrac{1}{2}(A_n + A_p) + 2 - \tfrac{1}{2}\ln(\beta_p/\beta_n) \tag{A13}$$

Combining (A8) and (A12) gives

$$-\xi_{n0}' \exp(-\xi_{n0}' - s) = 2a_n L_n \beta \tag{A14}$$

where

$$\beta = (\beta_n \beta_p)^{1/2}, \qquad s = \tfrac{1}{2}(s_n + s_p) \tag{A15}$$

and

$$a_n = (3L_n + L_p)/4L_n \tag{A16}$$

Similarly, one finds

$$-\xi_{p0}' \exp(-\xi_{p0}' - s) = 2a_p L_p \beta \tag{A17}$$

where

$$\xi_p' = \xi_p - s - \tfrac{1}{2} \ln (\beta_n/\beta_p) \tag{A18}$$

and

$$a_p = (L_n + 3L_p)/4L_p \tag{A19}$$

Substituting (A14) and (A17) into (A1) then gives

$$\begin{aligned} Z_m T &= (\xi_{n0}'/a_n)\,(\xi_{n0}'/a_n - 2)/L_n \\ &= 4\beta \exp(\xi_{n0}' + s)\,[1 + L_n \beta \exp(\xi_{n0}' + s)] \end{aligned} \tag{A20}$$

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ENTROPY PRODUCTION AND OPTIMUM DEVICE DESIGN

W. H. CLINGMAN*

Summary—The problem of optimum design is analyzed in this paper by considering the relation between efficiency or coefficient of performance and the local entropy production at each temperature within the device. A general design is considered, assuming that the volume of the device may be divided into a finite number of regions such that within each region the material properties are continuous and differentiable functions of position. Thermal contact resistance is neglected at the boundary between two regions; if there is current flow between two regions, electrical contact resistance at the boundary is neglected.

The results of the calculations are presented graphically. Application of these results to various well-known semiconductors is discussed.

INTRODUCTION

MOST thermoelectric devices now are based on the thermocouple circuit illustrated in Fig. 1. When $T_1 > T_0$ some of the heat which flows through the device is converted to electrical energy which can be delivered to a load. Alternatively, an electrical current can

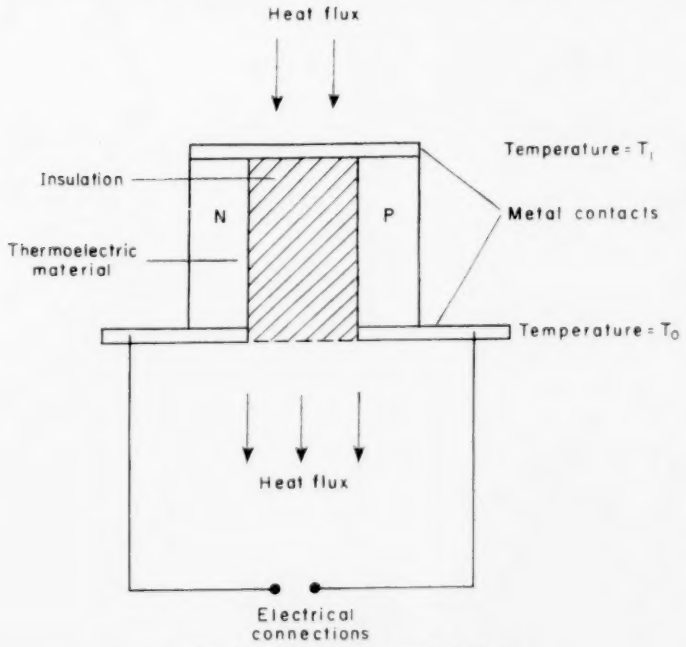

FIG. 1. Simple thermocouple design.

be applied to the device making $T_1 < T_0$ and pumping heat from the lower temperature to the higher. There is no reason *a priori* why the design in Fig. 1 should give optimum performance, i.e. maximum efficiency for generators or maximum coefficient of performance for coolers. A different arrangement of the thermoelectric materials, electrical connections,

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and thermal insulation between the heat source and heat sink might give a better device by using the thermoelectric effects better. For example, it is well known that staging thermocouples between the two operating temperatures improves performance [1].

The efficiency or coefficient of performance is very closely related to the concept of entropy production. Entropy is produced by the irreversible processes in the thermoelectric device. If these processes could be eliminated, entropy production would be reduced to zero, and the limiting Carnot efficiency or coefficient of performance would be obtained. Optimizing these latter quantities is closely related to minimizing the entropy production by varying device design.

In section 2 the relationship of efficiency and coefficient of performance to entropy production is derived. It is possible to express efficiency or coefficient of performance in terms of the ratio of entropy production in the device to the power output or input. These general concepts are applicable to any steady state heat engine and are not limited to thermoelectric device designs.

Following this general treatment, specific application to thermoelectric devices will be considered in section 3.

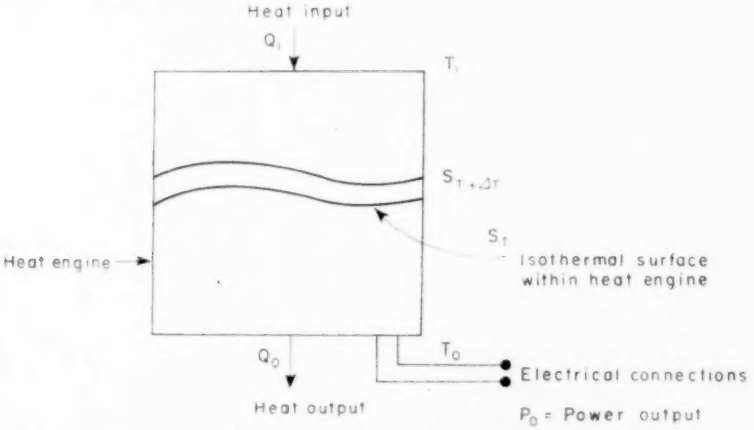

FIG. 2. Basic heat engine.

2. GENERAL THERMODYNAMIC TREATMENT

In this section the concept of entropy production will be applied to steady-state, static heat engines in general. The important features of the devices are shown in Fig. 2. Within the boundaries of the engine is some combination of thermoelectric material, electrical conductors, and insulation. A quantity of heat, Q_1, from a heat source enters the engine at a temperature T_1. A quantity of heat Q_0 is rejected from the engine at a temperature T_0 to a heat sink. There are electrical leads coming out of the device at the temperature T_0.

The basic problem is to vary the way in which a given set of thermoelectric materials is utilized within the box to obtain maximum efficiency. For this it is useful to relate these quantities to entropy production. The local entropy production within the device will be considered as a function of temperature, and the efficiency expressed in terms of this function.

Let P_0 = the power output of the engine when used as a generator and P_I = the power input when used as a heat pump. Generator efficiency and coefficient of performance of

heat pumps are defined as follows:

$$\text{Efficiency} = \eta = P_0/Q_1 \tag{1}$$

$$\text{Coefficient of performance} = \phi = Q_1/P_I \tag{2}$$

It is assumed that temperature is continuous throughout the heat engine volume. It is assumed that at each temperature T between T_1 and T_0 there is one and only one isothermal surface S_T. In appendix B it is shown that for the purpose of optimizing device design it is not necessary to consider cases where there is more than one isothermal surface corresponding to the same temperature. Let $\mathbf{n}_T$ be a unit vector normal to S_T and pointing in the direction of decreasing temperature. Let $\mathbf{F} = -\bar{\mu}/e\mathbf{J}$, where $\mathbf{J}$ is the current density, $\bar{\mu}$ the electrochemical potential, and e the electronic charge. $\mathbf{F}$ is then the flux of free energy which is carried by the electron current at any point. These vectors and those which are introduced below are to be considered as functions of position within the heat engine.

Let

$$F(T) = \int_{S_T} \mathbf{F} \cdot \mathbf{n}_T \, ds \tag{3}$$

$F(T)$ is the total flow of free energy which is carried by the electron current across S_T. It is assumed that $F(T)$ is a continuous and differentiable function of T. The next section shows that this assumption is satisfied for thermoelectric devices such that: (1) within the volume V of the heat engine there are a finite number of regions, where in each region the material properties are continuous and differentiable functions of positions; (2) there is no thermal or electrical contact resistance between regions.

Since there is no electron current crossing S_{T_1}, $F(T_1) = 0$. In generators $F(T_0)$ equals the total free energy delivered to the load by the electron current per unit time. Since all the electrical energy delivered to the load can be reversibly converted to work, $F(T_0) = P_0$. Similarly, in the case of heat pumps, $F(T_0) = P_I$.

Let

$$\frac{dF(T)}{dT} = -\,\mathrm{p}(T) \tag{4}$$

If ΔT is small, $\mathrm{p}(T)\Delta T$ can be considered as the portion of the electrical output produced by the materials between S_T and $S_{T+\Delta T}$.

Generally, for generators $\mathrm{p}(T) > 0$ and for heat pumps $\mathrm{p}(T) < 0$, since in the latter case electrical power is consumed within the heat engine.

$$\int_{T_0}^{T_1} \mathrm{p}(T)\, dT = P_0 \quad \text{(for generators)} \tag{5}$$

$$-\int_{T_1}^{T_0} \mathrm{p}(T)\, dT = P_I \quad \text{(for heat pumps)}$$

Let

$$J_s(T) = \int_{S_T} \mathbf{J}_s \cdot \mathbf{n}_T \, ds, \quad \text{where } \mathbf{J}_s \text{ equals entropy flux} \tag{6}$$

and

$$w(T) = \int_{S_T} \mathbf{w} \cdot \mathbf{n}_T \, ds, \quad \text{where } \mathbf{w} \text{ equals total energy flux} \tag{7}$$

$J_s(T)$ is the total flow of entropy and $w(T)$ the total flow of energy across S_T. Entropy

flux is given by the following equation [2]:

$$\mathbf{J}_s = 1/T(\mathbf{w} + \bar{\mu}/e\,\mathbf{J}) \tag{8}$$

Thus:

$$J_s(T) = 1/T[w(T) - F(T)] \tag{9}$$

Since the system is in a steady state, the total energy flow across S_T is independent of T. Since $F(T)$ is continuous and differentiable, it follows from equation (9) that $J_s(T)$ is also continuous and differentiable.

Let

$$\frac{\mathrm{d}J_s(T)}{\mathrm{d}T} = -\sigma(T) \tag{10}$$

If ΔT is small, $\sigma(T)\Delta T$ is the rate of entropy production due to irreversible processes occurring between S_T and $S_{T+\Delta T}$. $\sigma(T)$ is greater than zero for both generators and heat pumps.

$$\left.\begin{aligned} &\int_{T_0}^{T_1} \sigma(T)\,\mathrm{d}T = \Sigma = \text{total entropy production for generators;} \\ &\int_{T_1}^{T_0} \sigma(T)\,\mathrm{d}T = \Sigma = \text{total entropy production for heat pumps} \end{aligned}\right\} \tag{11}$$

Efficiency and coefficient of performance will now be related to

$$\int_{T_0}^{T_1} \frac{\epsilon(T)}{T}\,\mathrm{d}T,$$

where

$$\epsilon(T) = \frac{1}{1 + T\sigma(T)/\mathrm{p}(T)} = \frac{\mathrm{p}(T)}{\mathrm{p}(T) + T\sigma(T)} \tag{12}$$

For generators, define the function $\eta(T)$ as

$$\eta(T) = \frac{F(T)}{Q_1} \tag{13}$$

Then $\eta(T_1) = 0$ and $\eta(T_0) = \eta =$ efficiency.

Since $w(T)$ is independent of T, $w(T) = Q_1$; differentiating equation (9) with respect to T gives:

$$\mathrm{p}(T) + T\sigma(T) = 1/T[Q_1 - F(T)] = J_s(T) \tag{14}$$

It now follows from (12), (13), and (14) that

$$\frac{\mathrm{d}}{\mathrm{d}T} \ln\,[\eta(T) - 1] = \frac{\epsilon(T)}{T} \tag{15}$$

Integrating (15) between T_1 and T_0 gives

$$\eta = 1 - \exp\left[-\int_{T_0}^{T_1} \frac{\epsilon(T)}{T}\,\mathrm{d}T\right] \tag{16}$$

This is the desired equation relating the efficiency to the ratio, $\sigma(T)/\mathrm{p}(T)$, through the function $\epsilon(T)$.

Since $\sigma(T) > 0$ and $J_s(T_1) > 0$, it follows that $J_s(T) > 0$. Thus,

$$[w(T) - F(T)] = [Q_1 - F(T)] > 0$$

and $\epsilon(T) < 1$. Maximizing efficiency is equivalent to maximizing $\epsilon(T)$ or minimizing $\left| \sigma(T)/\mathrm{p}(T) \right|$ at each temperature.

A similar derivation for coolers gives:

$$\phi = 1 \Big/ \left\{ \exp \left[\int_{T_1}^{T_0} \frac{\epsilon(T)}{T} \, dT \right] - 1 \right\} \tag{17}$$

This is the relation for coolers analogous to equation (16).

In this case $J_s(T) < 0$ and $\sigma(T) > 0$. Therefore $\mathrm{p}(T) < 0$, $-1/T[Q_1 - F(T)] < 0$, and $\epsilon(T) > 1$. Maximizing coefficient of performance is equivalent to minimizing $\epsilon(T)$ or minimizing $\left| \sigma(T)/\mathrm{p}(T) \right|$ at each temperature.

Equations (16) and (17) enable design optimization to be considered independently at each temperature between T_1 and T_0. One can consider the design at each temperature T, which will minimize entropy production per unit power. This is opposed to having to consider the device as a whole.

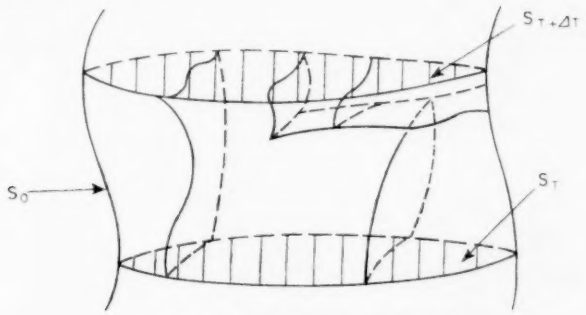

FIG. 3. Generalized thermoelectric device.

3. EVALUATION OF THERMOELECTRIC DEVICE PERFORMANCE

We will now consider evaluation of $\epsilon(T)$ in terms of material properties for thermoelectric devices. It will turn out that for any given set of materials and current distributions among these materials, there is an optimum value for the heat flux.

Figure 3 shows a cross-section of the general thermoelectric device to be considered. Within the cross-section are shown several regions which can be thermoelectric material, electrical conductors, or insulation. It is assumed that the device is composed of a finite number of such regions and that within each region the material parameters α, ρ, and κ are continuous and differentiable functions of the position vector $\mathbf{r}$. The Seebeck coefficient is α; the resistivity ρ; and thermal conductivity κ. These parameters may be discontinuous across a boundary between two regions.

Within each region the relationship of the entropy, current, and heat fluxes to the material parameters may be derived by irreversible thermodynamics [3]. These are as follows:

$$J_s = \alpha \mathbf{J} - 1/T\kappa \nabla T \tag{18}$$

$$\nabla(\bar{\mu}/e) = \rho \mathbf{J} - \alpha \nabla T \tag{19}$$

$$\operatorname{div} \mathbf{Q} = \rho \mathbf{J} \cdot \mathbf{J} - T \nabla \alpha \cdot \mathbf{J}, \quad \text{where } \mathbf{Q} = -\kappa \nabla T \tag{20}$$

Since the system is in a steady state, we also have:

$$\operatorname{div} \mathbf{J} = 0 \tag{21}$$

Let $\mathbf{N}_{AB}$ be a unit vector perpendicular to the boundary surface between two materials, A and B, pointing in the direction of B. Let $\mathbf{N}_0$ be a unit vector perpendicular to the surface S_0. At the boundary surface,

$$\mathbf{J}^A \cdot \mathbf{N}_{AB} = \mathbf{J}^B \cdot \mathbf{N}_{AB} \tag{22}$$

$$(\mathbf{Q}^A \cdot \mathbf{N}_{AB} - \mathbf{Q}^B \cdot \mathbf{N}_{AB}) = T(\alpha^B - \alpha^A)\, \mathbf{J}^A \cdot \mathbf{N}_{AB} \tag{23}$$

We can now derive a general expression for $\epsilon(T)$ in terms of the material parameters and the vector functions $\mathbf{J}(\mathbf{r})$ and $\mathbf{Q}(\mathbf{r})$.

$$\epsilon(T) = \frac{\mathrm{p}(T)}{\mathrm{p}(T) + T\sigma(T)} = \frac{\mathrm{p}(T)}{J_s(T)} \tag{12}$$

From equation (18) it follows that

$$\left.\begin{aligned} J_s(T) &= \int_{S_T} [1/T \mid \mathbf{Q} \mid + \alpha(\mathbf{J} \cdot \mathbf{n}_T)]\, \mathrm{d}s \\ \mathrm{p}(T) &= -\frac{\mathrm{d}F(T)}{\mathrm{d}T} = -\frac{\mathrm{d}}{\mathrm{d}T} \int_{S_T} \mathbf{F} \cdot \mathbf{n}_T\, \mathrm{d}s \end{aligned}\right\} \tag{24}$$

Appendix B shows that

$$-\frac{\mathrm{d}}{\mathrm{d}T} \int_{S_T} \mathbf{F} \cdot \mathbf{n}_T\, \mathrm{d}s = \int_{S_T} \frac{1}{\mid \nabla T \mid} \operatorname{div} \mathbf{F}\, \mathrm{d}s \tag{25}$$

$\operatorname{div} \mathbf{F} = \nabla\tilde{\mu}/e \cdot \mathbf{J}$, since $\operatorname{div} \mathbf{J} = 0$.

Thus, from (19) it follows that

$$\mathrm{p}(T) = \int_{S_T} \frac{1}{\mid \nabla T \mid} [\rho \mathbf{J} \cdot \mathbf{J} - \alpha \nabla T \cdot \mathbf{J}]\, \mathrm{d}s \tag{26}$$

Since $\mathbf{Q} = -\kappa \nabla T$ and $\mathbf{n}_T = -\nabla T / \mid \nabla T \mid$, combining equations (24) and (26) gives

$$\epsilon(T) = \frac{\displaystyle\int_{S_T} [\alpha(\mathbf{J} \cdot \mathbf{n}_T) - \frac{1}{\mid \mathbf{Q} \mid} (\rho\kappa)\, (\mathbf{J} \cdot \mathbf{J})]\, \mathrm{d}s}{\displaystyle\int_{S_T} [1/T \mid \mathbf{Q} \mid + \alpha(\mathbf{J} \cdot \mathbf{n}_T)]\, \mathrm{d}s} \tag{27}$$

This equation is a general result for any thermoelectric device satisfying the assumptions associated with Fig. 3. It enables evaluation of efficiency or coefficient of performance for a wide class of device designs. If the material properties are given as a function of position within the device, then the vector functions, $\mathbf{J}(\mathbf{r})$ and $\mathbf{Q}(\mathbf{r})$ which are needed to evaluate (27) may be determined from equations: (20), (21), (22), and (23).

We will now consider the problem of determining the optimum value of $\epsilon(T)$ for any given set of materials. In the next section specific device designs will be considered, allowing one to achieve or approach this optimum value.

Generally $\mid \mathbf{Q} \mid$ is a function of the position vector $\mathbf{r}$ along the surface S_T. Also α, $(\rho\kappa)$, and $\mathbf{J}$ are functions of $\mathbf{r}$. If the latter three functions are assumed given, then there is a

function $|\mathbf{Q}|_0$ which will optimize $\epsilon(T)$. Let $\epsilon_G(T)$ equal the optimum function in the case of generators and $\epsilon_c(T)$ equal the same for coolers. For any given set of materials and current distribution, $|\mathbf{Q}|$ may not have its optimum value $|\mathbf{Q}|_0$. In this case, $\epsilon_G(T)$ will be an upper limit for $\epsilon(T)$ in the case of generators and $\epsilon_c(T)$ will be a lower limit for $\epsilon(T)$ in the case of coolers. Let us first evaluate $\epsilon_G(T)$

$$\epsilon_G(T) = \frac{\int_{S_T} \left[\alpha(\mathbf{J}\cdot\mathbf{n}_T) - \frac{1}{|\mathbf{Q}|_0}(\rho\kappa)(\mathbf{J}\cdot\mathbf{J})\right] ds}{\int_{S_T} \left[1/T\,|\mathbf{Q}|_0 + \alpha(\mathbf{J}\cdot\mathbf{n}_T)\right] ds} \tag{28}$$

Determination of $|\mathbf{Q}|_0$ as a function of $\mathbf{r}$ is a problem in the calculus of variations. Applying the theorem derived in Appendix C to (28) gives

$$\epsilon_G(T) = \left\{ \frac{\partial/\partial\,|\mathbf{Q}|\left[\alpha(\mathbf{J}\cdot\mathbf{n}_T) - \frac{1}{|\mathbf{Q}|}(\rho\kappa)(\mathbf{J}\cdot\mathbf{J})\right]}{\partial/\partial\,|\mathbf{Q}|\left[1/T\,|\mathbf{Q}| + \alpha(\mathbf{J}\cdot\mathbf{n}_T)\right]} \right\}_{|\mathbf{Q}|=|\mathbf{Q}|_0} \tag{29}$$

Equation (29) reduces to

$$|\mathbf{Q}|_0 = \left[\frac{T}{\epsilon_G}\right]^{1/2} (\rho\kappa)^{1/2}\,|\mathbf{J}| = |\mathbf{Q}|_G \tag{30}$$

Substituting (30) back into (28) and making use of the fact that T and $\epsilon_G(T)$ are independent of position on the surface S_T gives:

$$\epsilon_G(T) = \frac{T^{1/2}\int_{S_T} \alpha(\mathbf{J}\cdot\mathbf{n}_T)\,ds - \epsilon_G{}^{1/2}\int_{S_T} (\rho\kappa)^{1/2}\,|\mathbf{J}|\,ds}{T^{1/2}\int_{S_T} \alpha(\mathbf{J}\cdot\mathbf{n}_T)\,ds + \epsilon_G{}^{-1/2}\int_{S_T} (\rho\kappa)^{1/2}\,|\mathbf{J}|\,ds} \tag{31}$$

Let

$$Z(T) = \frac{\left[\int_{S_T} \alpha(\mathbf{J}\cdot\mathbf{n}_T)\,ds\right]^2}{\left[\int_{S_T} (\rho\kappa)^{1/2}\,|\mathbf{J}|\,ds\right]^2} \tag{32}$$

Equation (31) can now be solved for ϵ_G as follows:

$$\epsilon_G = \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+1} = \text{optimum value of } \epsilon(T) \text{ for generators.} \tag{33}$$

In the case of coolers, equations (30) and (33) become:

$$|\mathbf{Q}|_0 = \left(\frac{T}{\epsilon_c}\right)^{1/2} (\rho\kappa)^{1/2}\,|\mathbf{J}| = |\mathbf{Q}|_c \tag{34}$$

$$\epsilon_c = \frac{\sqrt{1+ZT}+1}{\sqrt{1+ZT}-1} = \text{optimum value of } \epsilon(T) \text{ for coolers.} \tag{35}$$

Because of the relations (20) and (23) between $\mathbf{J}$ and $\mathbf{Q}$, it is not always possible to

achieve $|\mathbf{Q}|_0$ for any arbitrary distribution of current density. In this case, $\epsilon < \epsilon_G$ for generators and $\epsilon > \epsilon_c$ for coolers.

The function $Z(T)$, defined in equation (32), can be considered a generalized figure of merit for the thermoelectric device at each temperature T. If $|\mathbf{Q}| = |\mathbf{Q}|_0$, increasing $Z(T)$ results in better performance for both generators and coolers. It is interesting to note that $Z(T)$ depends not only on α and $(\rho\kappa)$ of the materials used at the temperature T, but also on the distribution of current among these materials. In the next section two-material thermoelectric devices will be considered, for which $Z(T)$ reduces to the usual Joffé figure of merit.

4. TWO-MATERIAL THERMOELECTRIC DEVICES

(*A*) *Definition*

The following assumptions define a two-material thermoelectric device. Consider the case where S_T intersects only two thermoelectric materials, 1 and 2. The surface S_T is composed of three parts, S_T^1, S_T^2, and S_T^R. S_T^1 and S_T^2 are the intersections with materials 1 and 2 respectively. It is also assumed that current may flow through electrical conductors intersecting S_T^R, but that α and $(\rho\kappa)$ are such that the integrals over S_T^R may be neglected in (32). It is assumed that α, $(\rho\kappa)$, $\mathbf{J}$ and $\mathbf{Q}$ are independent of position in either S_T^1 or S_T^2. In material 1, $(\mathbf{J} \cdot \mathbf{n}_T)_1 = |\mathbf{J}|_1$, and in material 2, $(\mathbf{J} \cdot \mathbf{n}_T)_2 = -|\mathbf{J}|_2$.
Let

$$A_1 = \int_{S_T^1} ds; \quad A_2 = \int_{S_T^2} ds.$$

Now assume $A_1 |\mathbf{J}|_1 = A_2 |\mathbf{J}|_2 = I =$ current through the device. When the above assumptions are satisfied,

$$Z(T) = \frac{(\alpha_1 - \alpha_2)^2}{[(\rho\kappa)_1^{1/2} + (\rho\kappa)_2^{1/2}]^2} = Z_0(T) \tag{36}$$

This is the conventional formula for thermocouple figure of merit. In order for $\epsilon(T)$ to equal $\epsilon_G(T)$ under the above assumptions it is necessary that

$$\left.\begin{aligned} |\mathbf{Q}|_i &= (T/\epsilon_G)^{1/2} (\rho\kappa)_i^{1/2} |\mathbf{J}|_i \quad \text{for generators} \\ |\mathbf{Q}|_i &= (T/\epsilon_c)^{1/2} (\rho\kappa)_i^{1/2} |\mathbf{J}|_i \quad \text{for coolers} \end{aligned}\right\} \tag{37}$$

where

$$\epsilon_G = \frac{\sqrt{1 + Z_0T} - 1}{\sqrt{1 + Z_0T} + 1}; \qquad \epsilon_c = \frac{\sqrt{1 + Z_0T} + 1}{\sqrt{1 + Z_0T} - 1}$$

Two-material thermoelectric device designs for which the conditions in equations (37) are realized or approximated will now be discussed.

(*B*) *Infinite staging*

With a two-material device an infinite number of stages with independent electrical outputs are used between the extreme temperatures T_1 and T_0. The current through each stage is controlled independently by means of electrical conductors which pass through S_T^R and satisfy the above assumptions. The current and area ratio of the legs are adjusted at each stage so that equation (37) is satisfied for each temperature between T_1 and T_0.

With (37) satisfied the expressions for efficiency and coefficient of performance become

$$\eta = 1 - \exp\left[-\int_{T_0}^{T_1} \frac{1}{T} \cdot \frac{\sqrt{1 + Z_0 T} - 1}{\sqrt{1 + Z_0 T} + 1}\, dT\right] \tag{38}$$

$$\phi = 1 \Big/ \left\{ \exp\left[\int_{T_1}^{T_0} \frac{1}{T} \cdot \frac{\sqrt{1 + Z_0 T} + 1}{\sqrt{1 + Z_0 T} - 1}\, dT\right] - 1 \right\} \tag{39}$$

These are the usual equations for infinite staging that are derived by other methods.

(C) Optimum Thomson coefficient

In this section we shall show that for any given values of Z and $(\rho\kappa)$, there is an optimum value of the Thomson coefficient, τ, which will result in (37) being satisfied. If the materials 1 and 2 possess optimum values of τ at each temperature, then the efficiency or coefficient of performance is given by (38) or (39). With this material, for which τ is optimized, a single stage device gives the same performance as an infinitely staged one.
The optimum Thomson coefficients for the two materials are for generators:

$$\left.\begin{aligned} \tau_1 &= -\frac{\partial}{\partial T}\left[\frac{T(\rho\kappa)_1}{\epsilon_G}\right]^{1/2} - \left[\frac{\epsilon_G(\rho\kappa)_1}{T}\right]^{1/2} \\ \tau_2 &= \frac{\partial}{\partial T}\left[\frac{T(\rho\kappa)_2}{\epsilon_G}\right]^{1/2} + \left[\frac{\epsilon_G(\rho\kappa)_2}{T}\right]^{1/2} \end{aligned}\right\} \tag{40}$$

With coolers, similar equations apply with ϵ_c substituted for ϵ_G. The general equation which the heat flux must satisfy in each material is:

$$\frac{d\,|\,\mathbf{Q}\,|_i}{dT} = -\frac{(\rho\kappa)_i\,|\,\mathbf{J}\,|_i^2}{|\,\mathbf{Q}\,|_i} - \tau_i(\mathbf{J}\cdot\mathbf{n}_T)_i \tag{41}$$

Where

$$\tau_i = T\frac{\partial \alpha_i}{\partial T}, \quad (\mathbf{J}\cdot\mathbf{n}_T)_1 = |\,\mathbf{J}\,|_1, \quad \text{and } (\mathbf{J}\cdot\mathbf{n}_T)_2 = -|\,\mathbf{J}\,|_2.$$

When τ_i has the values given in (40), then a particular solution of (41) is

$$|\,\mathbf{Q}\,|_i = \left(\frac{T}{\epsilon_G}\right)^{1/2} (\rho\kappa)_i^{1/2}\,|\,\mathbf{J}\,|_i \tag{37}$$

We shall now determine the design criteria for the size of the legs and the load resistance so that (37) also satisfies the boundary conditions. These will be expressed in terms of the load resistance, R_L, and the resistances of the two legs R_1 and R_2. Under the assumptions for a two-material device, the leg resistance, R_i, can be expressed as follows:

$$R_i = \frac{1}{A_i\,|\,\mathbf{J}\,|_i}\int_{T_0}^{T_1} \frac{(\rho\kappa)_i}{|\,\mathbf{Q}\,|_i}\,|\,\mathbf{J}\,|_i\,dT \tag{42}$$

If $|\,\mathbf{Q}\,|_i$ has its optimum value given by equation (37), the design condition on the size of the legs is

$$\frac{R_1}{R_2} = \frac{\displaystyle\int_{T_0}^{T_1}\left(\frac{\epsilon_G}{T}\right)^{1/2}(\rho\kappa)_1^{1/2}\,dT}{\displaystyle\int_{T_0}^{T_1}\left(\frac{\epsilon_G}{T}\right)^{1/2}(\rho\kappa)_2^{1/2}\,dT} \tag{43}$$

Let

$R_G = R_1 + R_2 =$ total generator resistance

$V =$ open circuit voltage

$$\left.\begin{aligned} V &= \int_{T_0}^{T_1} (a_1 - a_2)\, dT = I(R_G + R_L) \\ R_G I &= \int_{T_0}^{T_1} \left(\frac{\epsilon_G}{T}\right)^{1/2} [(\rho\kappa)_1^{1/2} + (\rho\kappa)_2^{1/2}]\, dT \end{aligned}\right\} \tag{44}$$

Then

$$\frac{R_G}{R_G + R_L} = \frac{\int_{T_0}^{T_1} (a_1 - a_2) \left[\frac{1}{1 + \sqrt{1 + Z_0 T}}\right] dT}{\int_{T_0}^{T_1} (a_1 - a_2)\, dT} \tag{45}$$

If the resistances are such that (43) and (45) are satisfied, and the Thomson coefficients have the values given by (40) at each temperature, then the heat fluxes, $| \mathbf{Q} |_t$, will have their optimum values. In this case the same efficiency will be obtained with a single stage device as with an infinite-stage device.

For coolers, the design condition on the size of the legs is still (43) and the optimum Thomson coefficients become:

$$\left.\begin{aligned} \tau_1 &= -\frac{\partial}{\partial T} [T(\rho\kappa)_1/\epsilon_c]^{1/2} - [\epsilon_c(\rho\kappa)_1/T]^{1/2} \\ \tau_2 &= \frac{\partial}{\partial T} [T(\rho\kappa)_2/\epsilon_c]^{1/2} + [\epsilon_c(\rho\kappa)_2/T]^{1/2} \end{aligned}\right\} \tag{46}$$

Equation (44) becomes:

$$R_G I = \int_{T_1}^{T_0} \left(\frac{\epsilon_c}{T}\right)^{1/2} [(\rho\kappa)_1^{1/2} + (\rho\kappa)_2^{1/2}]\, dT \tag{47}$$

and we have

$$I = \frac{1}{R_G} \int_{T_1}^{T_0} (a_1 - a_2) \left[\frac{1}{\sqrt{1 + Z_0 T} - 1}\right] dT \tag{48}$$

Equation (48) gives the current for maximum coefficient of performance when the Thomson coefficients have their optimum values at each temperature.

(*D*) *Numerical examples*

Numerical calculations to compare the optimum design with single stage designs were made to illustrate some of the general principles discussed above. A cooler made from material with a constant value of ZT equal to 1, a bismuth telluride cooler, and a lead teluride generator are described. It is characteristic of two-material device designs that the optimum values of η, ϕ and $| \mathbf{Q} |/| \mathbf{J} |$ depend only on the materials used at each temperature. For the bismuth telluride cooler and lead telluride generator the optimum values of the heat

flux-current density ratio ($|\mathbf{Q}|/|\mathbf{J}|$) are compared with the actual values in a single-stage device.

In Fig. 4, coefficient of performance is plotted against temperature difference for a cooler made from material with a constant value of Z_0T equal to one and a Thomson coefficient of zero. The hot junction is kept at 300°K. At each operating point the current and

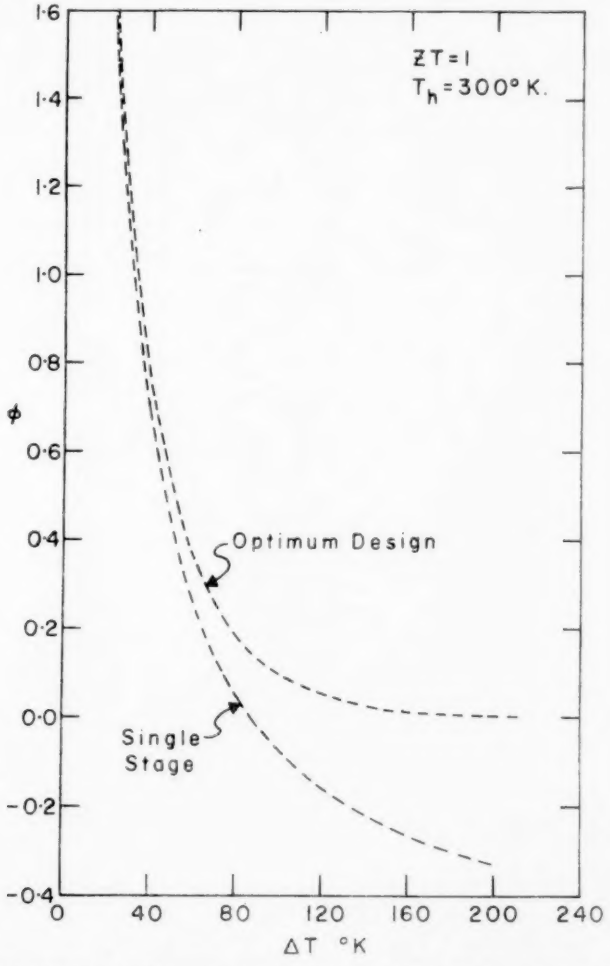

FIG. 4. Coefficient of performance vs. temperature difference for constant $ZT = 1$.

the dimensions of the legs are chosen so as to maximize the coefficient of performance. The curve for the single-stage device was calculated by solving the differential equation for the temperature distribution in the thermoelements. It crosses the $\phi = 0$ axis at a ΔT of 87°C. This is the maximum value of ΔT that can be obtained with a single-stage design. When the device is operated between 300°K and an environment at a lower temperature than 213°K, heat will flow into the low temperature environment rather than out of it, then the coefficient of performance is negative.

The significant part of the optimum design curve (equation (39)) in Fig. 4 is that it does not cross the $\phi = 0$ axis. There is no uniquely defined maximum value for ΔT. Thus, lower temperatures can be achieved with the optimum design. Also when the single-stage design is operating close to its maximum temperature difference, significant improvements in coefficient of performance can be made by using the optimum design.

It is known [4, 5] that the optimum design can be obtained by infinite staging. The latter enables us to obtain the optimum heat flux-current density ratio at each temperature in the device. There are also other design possibilities for optimizing this ratio, and these give

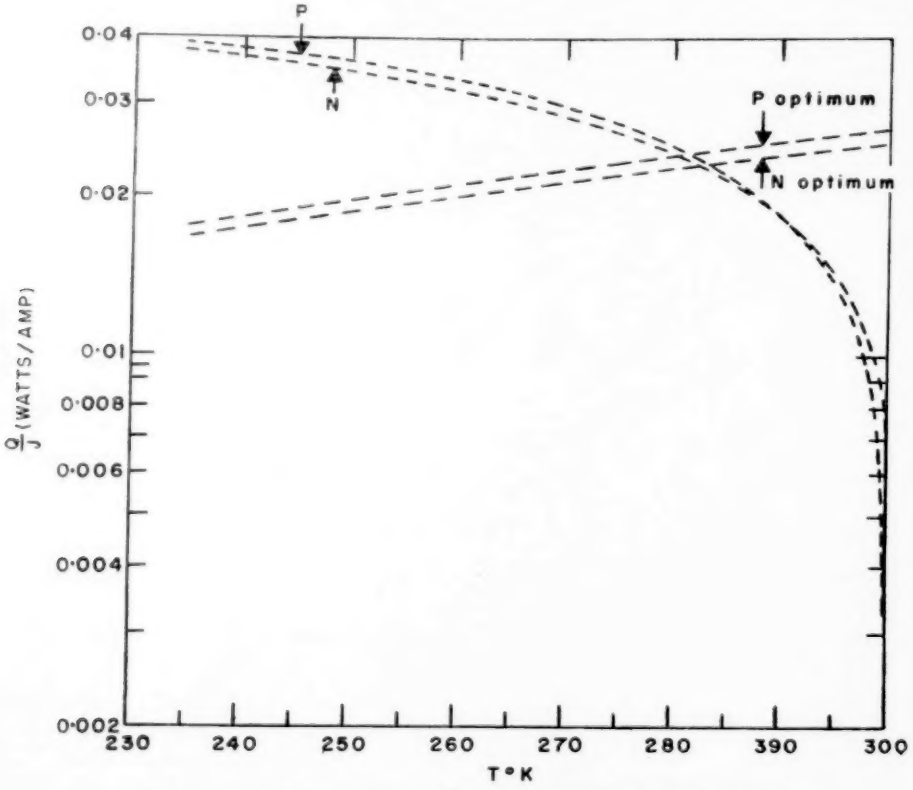

FIG. 5. Heat flux to current density ratio vs. cold junction temperature for a bismuth telluride peltier cooler.

the same device performance as infinite staging. For example, if Z_0T has a constant value of one, but the Thomson coefficient has its optimum value rather than zero, the single-stage curve will coincide with the optimum design curve in Fig. 4.

Figure 5 compares the heat flux-current density ratio for a Peltier cooler with its optimum value. The properties of the bismuth telluride used in this cooler are given in Table 1, and the design characteristics of the device are in Table 2. The current chosen enabled the device to operate very close to its maximum value of ΔT. The actual thermocouple performance was calculated using a 704 computer program [6]. The optimum design gives a coefficient of performance of 0·143 while that of the single-stage design is only 0·0062.

TABLE 1. BISMUTH TELLURIDE ALLOY PROPERTIES

	n-Type			*p*-Type		
Temperature (°K)	α, μV/deg	ρ, ohm-cm	κ, W/cm-deg	α, μV/deg	ρ, ohm-cm	κ, W/cm-deg
240	−168	$6{\cdot}0\times10^{-4}$	0·0212	168	$8{\cdot}3\times10^{-4}$	0·0174
250	−173	$6{\cdot}4\times10^{-4}$	0·0206	174	$8{\cdot}9\times10^{-4}$	0·0168
260	−178	$6{\cdot}8\times10^{-4}$	0·0201	180	$9{\cdot}4\times10^{-4}$	0·0163
270	−184	$7{\cdot}3\times10^{-4}$	0·0196	186	$9{\cdot}9\times10^{-4}$	0·0159
280	−189	$7{\cdot}8\times10^{-4}$	0·0192	191	$10{\cdot}6\times10^{-4}$	0·0156
290	−194	$8{\cdot}2\times10^{-4}$	0·0189	196	$11{\cdot}4\times10^{-4}$	0·0153
300	−198	$8{\cdot}7\times10^{-4}$	0·0187	200	$12{\cdot}1\times10^{-4}$	0·0151
310	−201	$9{\cdot}1\times10^{-4}$	0·0186	204	$12{\cdot}9\times10^{-4}$	0·0150

TABLE 2. PELTIER COOLER PERFORMANCE

Material:	Bismuth Telluride Alloy (Table 1)
Areas:	*n*-leg 0·394 cm²; *p*-leg 0·412 cm²
Length:	1·33 cm
Current:	15·40 amp
Temperatures:	$T_h = 299{\cdot}7$°K; $T_c = 235{\cdot}2$°K; $\Delta T = 64{\cdot}5$°C
	Coefficient of Performance: 0·0062
	Optimum Design—Coefficient of performance = 0·143

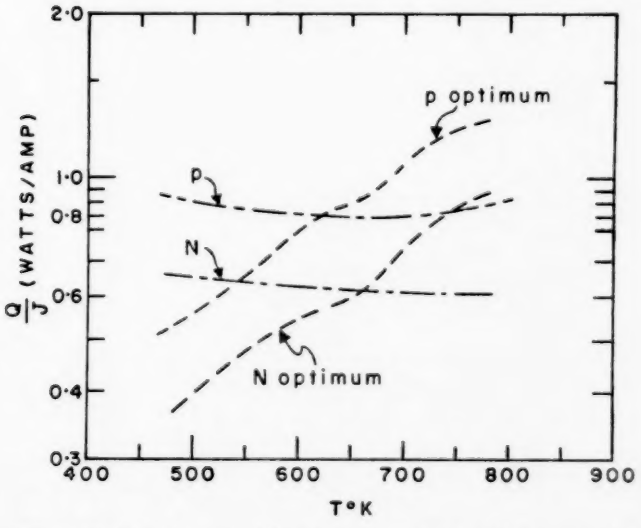

FIG. 6. Heat flux to current density ratio vs. hot junction temperature for a lead telluride Seebeck generator.

Similar curves are given in Fig. 6 for a lead telluride generator. In this case the optimum heat flux-current density ratio (equation (37)) does not deviate as markedly from the actual ratio for a single-stage design. The efficiency of the single-stage device is 6·07 per cent while that for optimum design with the same material is 6·68 per cent. A 704 computer

program [7] again calculated the performance for the single-stage design, using the data given in Table 3 and the design characteristics in Table 4.

TABLE 3. LEAD TELLURIDE PROPERTIES

n-Type 0·03% PbI_2; p-Type 0·3% Na

	n-Type			p-Type		
Temperature (°K)	α, μV/deg	ρ, ohm-cm	κ, W/cm-deg	α, μV/deg	ρ, ohm-cm	κ, W/cm-deg
373	170	$0{\cdot}700\times10^{-3}$	0·0240	180	$1{\cdot}20\times10^{-3}$	0·0200
473	200	$1{\cdot}30\times10^{-3}$	0·0213	250	$3{\cdot}50\times10^{-3}$	0·0180
573	230	$2{\cdot}70\times10^{-3}$	0·0195	330	$6{\cdot}00\times10^{-3}$	0·0170
623	245	$3{\cdot}20\times10^{-3}$	0·0187	350	$8{\cdot}00\times10^{-3}$	0·0167
673	250	$3{\cdot}70\times10^{-3}$	0·0185	340	$9{\cdot}00\times10^{-3}$	0·0165
723	250	$4{\cdot}60\times10^{-3}$	0·0183	300	$10{\cdot}00\times10^{-3}$	0·0166
773	240	$5{\cdot}00\times10^{-3}$	0·0182	260	$10{\cdot}00\times10^{-3}$	0·0167
873	210	$5{\cdot}20\times10^{-3}$	0·0130	160	$8{\cdot}00\times10^{-3}$	0·0170

TABLE 4. GENERATOR PERFORMANCE

Material:	Lead Telluride: n-type 0·03% P6I_2; p-type 0·3% Na
Areas:	n-leg 0·316 cm²; p-leg 0·504 cm²
Length:	1·00 cm
Load resistance:	0·0297 ohm
Current:	3·88 amp
Temperatures:	$T_h = 825$°K; $T_c = 425$°K
	Efficiency = 6·07%
	Optimum design efficiency = 6·68%

5. CONCLUSIONS

The optimum design of thermoelectric heat engines has been investigated by relating device performance to the local entropy production within the device. The effect of device design on this local entropy production is determined and the theory developed is sufficiently general to include a wide range of designs.

Given the materials that are available in any specified temperature range, one can calculate the maximum possible efficiency or coefficient of performance from the general theory. This maximum performance can be reached by infinite staging, but for certain values of the material parameters a single stage device will give the same performance as an infinitely staged one.

APPENDIX A

The Uniqueness of the Isothermal Surfaces

Let us assume that within the heat engine there are two isothermal surfaces at the same temperature, T_2, as shown in Fig. 7. Between the two surfaces temperatures other than T_2 may occur.

These isothermal surfaces divide the device into regions 1, 2, and 3. Now consider the total heat engine as made up of three individual heat engines coupled together, as shown in Fig. 8. Q_A is the total heat transferred from region 1 to region 2 in the original device, Fig. 7.

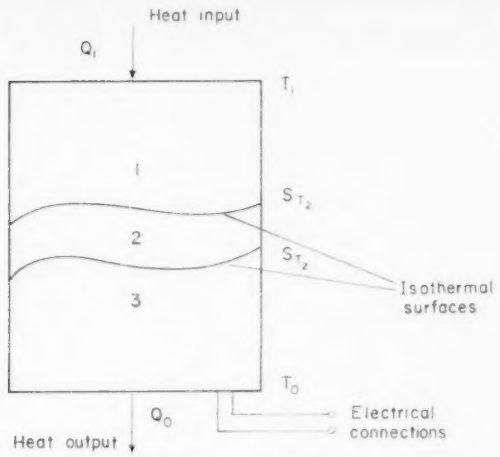

FIG. 7. Heat engine containing two isothermal surfaces at temperature T_2.

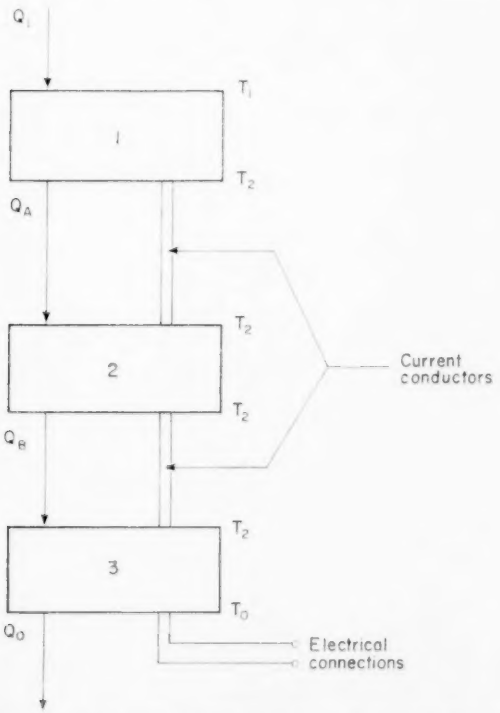

FIG. 8. Coupled heat engines equivalent to single heat engine of Fig. 7.

There is a current flow equal to I_A in both directions between these two regions. The current into region 1 must equal the current out since there is no charge accumulation. Similar quantities for the boundaries between regions 2 and 3 are Q_B and I_B. Let the subscript i refer to region i.

Then

$$\Sigma_2 = \frac{Q_B}{T_2} - \frac{Q_A}{T_2}$$

From the second law of thermodynamics it follows that $\Sigma_2 \geqslant 0$

$$\therefore \qquad Q_B \geqslant Q_A$$

Thus the net effect of region 2 is to convert electrical energy into heat energy. Thus, region 2 may be replaced with a four terminal resistive network held at the constant temperature T_2, as shown in Fig. 9. Even though thermoelectric effects may occur in region 2 of

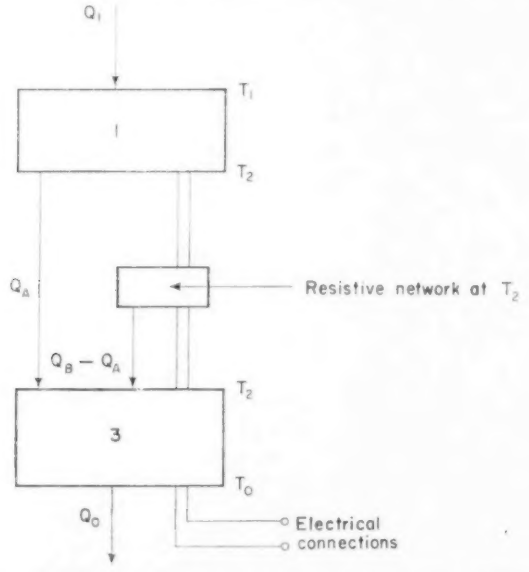

FIG. 9. Heat engines with region between isothermal surfaces replaced by a resistive network.

Fig. 8, this part of the device may be replaced with a passive resistance network with no loss in efficiency.

The significance of this conclusion is that for the purpose of optimizing device design it is only necessary to consider those cases where there is one and only one isothermal surface corresponding to any temperature between T_1 and T_0.

APPENDIX B

Temperature Derivative of the Free Energy Flow

In this appendix the validity of equation (25) is demonstrated.

$$-\frac{\mathrm{d}}{\mathrm{d}T}\int_{S_T} \mathbf{F}\cdot\mathbf{n}_T\,\mathrm{d}s = \int_{S_T} \frac{1}{|\nabla T|}\,\mathrm{div}\,\mathbf{F}\,\mathrm{d}s \tag{25}$$

We first prove the following general theorem which relates to the construction shown in Fig. 3. The same terminology is used as in the discussion of this figure in section 3.

Theorem

If $G(\mathbf{r})$ is a vector function that is continuous and differentiable within each region; $\mathbf{G}^A \cdot \mathbf{N}_{AB} = \mathbf{G}^B \cdot \mathbf{N}_{AB}$ for the boundary surface between any two regions A and B; $\mathbf{G} \cdot \mathbf{N}_0 = 0$, then

$$\frac{\partial}{\partial T} \int_{S_T} (\mathbf{G} \cdot \mathbf{n}_T)\, ds = - \int_{S_T} \frac{1}{|\nabla T|} (\operatorname{div} \mathbf{G})\, ds$$

Proof

Let

$$G(T) = \int_{S_T} (\mathbf{G} \cdot \mathbf{n}_T)\, ds$$

$$\frac{d}{dT} G(T) = \lim_{\Delta T \to 0} \frac{G(T + \Delta T) - G(T)}{\Delta T} \tag{B1}$$

Let ΔV equal the volume element bounded by S_T, $S_{T+\Delta T}$, and S_0. Let ΔV_i equal the volume of region i within ΔV. Since $\mathbf{G}^A \cdot \mathbf{N}_{AB} = \mathbf{G}^B \cdot \mathbf{N}_{AB}$ for the boundary between any two regions A and B, it follows from Gauss' theorem that

$$G(T + \Delta T) - G(T) = - \sum_i \int_{\Delta V_i} \operatorname{div} \mathbf{G}\, dv = - \int_{\Delta V} \operatorname{div} G\, dv \tag{B2}$$

since the surface integrals over all inter-region boundaries within ΔV cancel.

Let

$$\mathbf{A} = \frac{1}{|\nabla T|} (\operatorname{div} \mathbf{G})\, \mathbf{n}_T \tag{B3}$$

Then it follows that

$$- \int_{\Delta V_i} \operatorname{div} \mathbf{G}\, dv = \int_{\Delta V_i} \operatorname{div}(T\mathbf{A})\, dv - \int_{\Delta V_i} T \operatorname{div} \mathbf{A}\, dv \tag{B4}$$

The surface bounding each region i in ΔV is made up of three parts: S_T^i, which is part of S_T; $S_{T+\Delta T}^i$, which is part of $S_{T+\Delta T}$; S_B^i, which forms the remainder of the boundary of the volume element ΔV_i.

From the mean value theorem it follows that there exists a number, θ_i, such that $0 \leq \theta_i \leq$ and

$$\int_{\Delta V_i} T \operatorname{div} \mathbf{A}\, dv = (T + \theta_i \Delta T) \int_{\Delta V_i} \operatorname{div} \mathbf{A}\, dv \tag{B5}$$

The integrals on the right-hand side of (B4) may now be converted into surface integrals using Gauss's theorem:

$$\int_{\Delta V_i} \operatorname{div}(T\mathbf{A})\, dv = T \int_{S_T^i} \mathbf{A} \cdot \mathbf{n}_T\, ds - (T + \Delta T) \int_{S_{T+\Delta T}^i} \mathbf{A} \cdot \mathbf{n}_{T+\Delta T}\, ds + \int_{S_B^i} T\mathbf{A} \cdot d\mathbf{s} \tag{B6}$$

$$\int_{\Delta V_i} T \operatorname{div} \mathbf{A}\, dv = (T + \theta_i \Delta T) \left[\int_{S_T^i} \mathbf{A} \cdot \mathbf{n}_T\, ds - \int_{S_{T+\Delta T}^i} \mathbf{A} \cdot \mathbf{n}_{T+\Delta T}\, ds + \int_{S_B^i} \mathbf{A} \cdot d\mathbf{s} \right] \tag{B7}$$

It also follows from the mean value theorem that there exists a number ψ_i, such that $0 \leq \psi_i \leq$ and

$$\int_{S_B} T\mathbf{A} \cdot \mathrm{d}\mathbf{s} = (T + \psi_i \Delta T) \int_{S_B} \mathbf{A} \cdot \mathrm{d}\mathbf{s} \tag{B8}$$

Equations (B6), (B7) and (B8) can now be combined to give:

$$\frac{1}{\Delta T} \int_{\Delta V_i} \operatorname{div} \mathbf{G}\, \mathrm{d}v = \int_{S_{T+\Delta T}} \mathbf{A} \cdot \mathbf{n}_{T+\Delta T}\, \mathrm{d}s + \theta_i \int_{\Delta V_i} \operatorname{div} \mathbf{A}\, \mathrm{d}v - \psi_i \int_{S_B} \mathbf{A} \cdot \mathrm{d}\mathbf{s} \tag{B9}$$

We now evaluate the limit of the right-hand side of (B9) as ΔT approaches zero

$$\lim_{\Delta T \to 0} \frac{1}{\Delta T} \int_{\Delta V} \operatorname{div} \mathbf{G}\, \mathrm{d}v = \sum_i \int_{S_T} \mathbf{A} \cdot \mathbf{n}_T\, \mathrm{d}s = -\frac{\mathrm{d}G(T)}{\mathrm{d}T}$$

From (B3) it follows that:

$$\frac{\mathrm{d}G(T)}{\mathrm{d}T} = -\int_{S_T} \frac{1}{|\nabla T|} (\operatorname{div} \mathbf{G})\, \mathrm{d}s$$

The vector function $\mathbf{F}(\mathbf{r})$ satisfies the hypotheses of the above theorem. This is seen as follows: $\mathbf{F} \cdot \mathbf{N}_0 = 0$, since there is no current flow across S_0; $\mathbf{F}^A \cdot \mathbf{N}_{AB} = \mathbf{F}^B \cdot \mathbf{N}_{AB}$, since $\mathbf{F} = -\bar{\mu}/e\mathbf{J}$, $\bar{\mu}$ is continuous across the boundary between A and B if $\mathbf{J} \cdot \mathbf{N}_{AB} = 0$, and there is no charge accumulation at the boundary. Thus, equation (25) follows directly from the above theorem.

APPENDIX C

Note on the Calculus of Variations

The following theorem is useful in determining a formula for the optimum value of $\epsilon(T)$. The theorem is established by the usual techniques of the calculus of variations.

Theorem

If

$$f(\mathbf{r}) = f_0(\mathbf{r})$$

makes

$$\Phi = \left\{ \int_{S_T} G[f(\mathbf{r}), \mathbf{r}]\, \mathrm{d}s \right\} \Big/ \left\{ \int_{S_T} H[f(\mathbf{r}), \mathbf{r}]\, \mathrm{d}s \right\}$$

stationary, then

$$\Phi_0 = \frac{\int_{S_T} G[f_0(\mathbf{r}), \mathbf{r}]\, \mathrm{d}s}{\int_{S_T} H[f_0(\mathbf{r}), \mathbf{r}]\, \mathrm{d}s} = \frac{G_f[f_0(\mathbf{r}), \mathbf{r}]}{H_f[f_0(\mathbf{r}), \mathbf{r}]}$$

Proof

Let

$$h(\mathbf{r}, \beta) = f_0(\mathbf{r}) + \beta\eta(\mathbf{r}), \qquad \eta(\mathbf{r}_B) = 0$$

where $\mathbf{r}_B$ is on the boundary of the region S_T. Otherwise $\eta(\mathbf{r})$ is an arbitrary continuous and differentiable function defined over S_T.

Let

$$\Phi(\beta) = \frac{\int_{S_T} G[h(\mathbf{r}, \beta), \mathbf{r}]\, ds}{\int_{S_T} H[h(\mathbf{r}, \beta), \mathbf{r}]\, ds}$$

A necessary condition for Φ to be stationary with respect to the function $f(\mathbf{r})$ is that

$$\left[\frac{d}{d\beta}\Phi(\beta)\right]_{\beta=0} = 0$$

for all functions $\eta(\mathbf{r})$.

$$\left[\frac{d}{d\beta}\Phi(\beta)\right]_{\beta=0} = \frac{\left[\int_{S_T} H\, ds\right]\left[\int_{S_T} G_f\, \eta\, ds\right] - \left[\int_{S_T} G\, ds\right]\left[\int_{S_T} H_f\, ds\right]}{\left[\int_{S_T} H\, ds\right]^2} \tag{C1}$$

Since

$$\left[\int_{S_T} G\, ds\right] \Big/ \left[\int_{S_T} H\, ds\right] = \Phi_0,$$

it follows from (C1) that

$$\int_{S_T} \{G_f[f_0(\mathbf{r}), \mathbf{r}] - \Phi_0\, H_f[f_0(\mathbf{r}), \mathbf{r}]\}\, \eta(\mathbf{r})\, ds = 0 \tag{C2}$$

Since (C2) must be true for any arbitrary function $\eta(\mathbf{r})$,

$$G_f[f_0(\mathbf{r}), \mathbf{r}] - \Phi_0\, H_f[f_0(\mathbf{r}), \mathbf{r}] = 0 \tag{C3}$$

The desired conclusion follows immediately from (C3).

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MAXIMUM FIGURE OF MERIT OF THERMOELECTRIC MATERIALS*

R. SIMON†

Summary—An estimate of the maximum figure of merit at optimum carrier concentration of a thermoelectric material is shown to be obtainable from the measured values of the Seebeck coefficient, the electrical conductivity, and the thermal conductivity for any extrinsic specimen of the material that is not too greatly overdoped. Effects of minority carriers, impurity scattering, and multiband conduction on this estimate are discussed.

INTRODUCTION

THE PERFORMANCE of a thermoelectric material in a heat pump or in an electric-power generator is determined by the value of its figure of merit [1]

$$Z = \alpha^2\sigma/\kappa, \tag{1}$$

where α is the Seebeck coefficient, σ is the electrical conductivity, and κ is the thermal conductivity. The dimensionless figure of merit ZT, where T is the absolute temperature, is given by

$$ZT = A^2/K, \tag{2}$$

where $A \equiv |(e/k)\alpha|$ and $K \equiv (e/k)^2\,\kappa/\sigma T$ are also dimensionless parameters. The quantity $k/e = 86{\cdot}2 \times 10^{-6}$ V/deg is the ratio of Boltzmann's constant to the absolute magnitude of the electronic charge.

It is shown herein that the values of A, K and r for an extrinsic, but not necessarily optimized, specimen of a given thermoelectric material are sufficient information for determination of the value of $Z_{max}T$ for that material, where $Z_{max}T$ is the value of the figure of merit at optimum carrier concentration. The quantity r is the exponent in the assumed power-law variation of the mean free path of the charge carrier with its kinetic energy. The relationship among $Z_{max}T$, A, K and r is found to be relatively insensitive to variations in r for approximately optimum-doped or underdoped thermoelectric materials in the range of values of $Z_{max}T$ of present interest. Hence, a good estimate of $Z_{max}T$ is obtainable from the values of A and K alone for a single extrinsic specimen that is not too heavily overdoped. The values of A and K for an extrinsic specimen also furnish sufficient information to determine whether the specimen is underdoped, overdoped or doped to about optimum carrier concentrations for the material in question. If the specimen is either underdoped or overdoped, the amount of readjustment in doping needed to obtain an approximately optimized specimen is indicated in terms of the required change in the value of the Seebeck coefficient.

ANALYSIS AND RESULTS

For an extrinsic semiconductor with spherical constant-energy surfaces, A is given by

$$A(r, \eta) = \frac{r+2}{r+1}\frac{F_{r+1}(\eta)}{F_r(\eta)} - \eta, \tag{3}$$

* Research supported by the Thermoelectric Cooling Research Group.
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where η is the reduced Fermi energy (the Fermi energy in units of kT measured positively upward from the conduction-band minimum or positively downward from the valence-band maximum for n-type or p-type semiconductors, respectively), and $F_k(\eta)$ is the Fermi integral

$$\int_0^\infty x^k \, [1 + \exp(x - \eta)]^{-1} \, dx.$$

The electrical conductivity is given by

$$\sigma(r, \eta) = \sigma_0 F_r(\eta)/r!, \tag{4}$$

where $\sigma_0 = 2(2\pi m kT/h^2)^{3/2} \, e\mu_c$; m is the effective mass of the charge carrier; h is Planck's constant; and μ_c is the low-carrier-concentration value of the charge-carrier mobility. The thermal conductivity is

$$\kappa = \kappa_{ph} + (k/e)^2 \, L(r, \eta) \, \sigma T, \tag{5}$$

where κ_{ph} is the phonon contribution and $(k/e)^2 \, L(r, \eta)$ is the Lorenz number, with

$$L(r, \eta) = \frac{r + 3}{r + 1} \frac{F_{r+2}(\eta)}{F_r(\eta)} - \left[\frac{r + 2}{r + 1} \frac{F_{r+1}(\eta)}{F_r(\eta)}\right]^2. \tag{6}$$

Hence, the parameter K becomes

$$K(r, \eta) = [\beta F_r(\eta)/r!]^{-1} + L(r, \eta), \tag{7}$$

where

$$\beta = (k/e)^2 \, \sigma_0 T/\kappa_{ph}$$

is a dimensionless material parameter.

Equations (2), (3) and (7) may be combined to obtain ZT as a function of r, η and β as shown by Rittner [2] and by Chasmar and Stratton [3]. If it is assumed that both β and r are independent of carrier concentration,* maximization of ZT with respect to η results in

$$\begin{aligned} Z_{\max}T &= \frac{A^2(r, \eta_0)}{[\beta F_r(\eta_0)/r!]^{-1} + L(r, \eta_0)} \\ &= \frac{A^2(r, \eta_0) \, \dfrac{\partial}{\partial \eta} \ln [F_r(\eta_0) \, A^2(r, \eta_0)]}{L(r, \eta_0) \, \dfrac{\partial}{\partial \eta} \ln [F_r(\eta_0) \, L(r, \eta_0)]}, \end{aligned} \tag{8}$$

where η_0 is the optimum value of η. The quantities $Z_{\max}T$ and η_0 as functions of β and r are readily obtained from equation (8) by inserting various values of η_0 and computing $Z_{\max}T$ and β. The partial derivatives with respect to η are evaluated by using the relationships

$$\frac{\partial}{\partial \eta} F_k(\eta) = kF_{k-1}(\eta) \quad \text{and} \quad \frac{\partial}{\partial \eta} F_0(\eta) = [1 + \exp(-\eta)]^{-1}.$$

Figure 1 shows $Z_{\max}T$ as a function of $\beta \exp r$ for $r = -1$, 0, 1, and 2, as obtained from Chasmar and Stratton's curves and from equation (8). It is seen that the value of $Z_{\max}T$ is a monotonically increasing function primarily of the combination $\beta \exp r$ of

* Effects of deviations from this assumption will be discussed later.

the two parameters β and r. This functional relationship is almost entirely independent of the explicit value of r in the vicinity of $Z_{\max}T = 1$, in which neighborhood are found the values of $Z_{\max}T$ attainable with presently available thermoelectric materials of good quality. For $r = -1$, equations (3), (4) and (6) become

$$A(-1, \eta) = [1 + \exp(-\eta)]\, F_0(\eta) - \eta,$$
$$\sigma(-1, \eta) = \sigma_0[1 + \exp(-\eta)]^{-1}, \quad \text{and} \quad L(-1, \eta)$$
$$= 2[1 + \exp(-\eta)]\, F_1(\eta) - \{[1 + \exp(-\eta)]\, F_0(\eta)\}^2,$$

respectively.

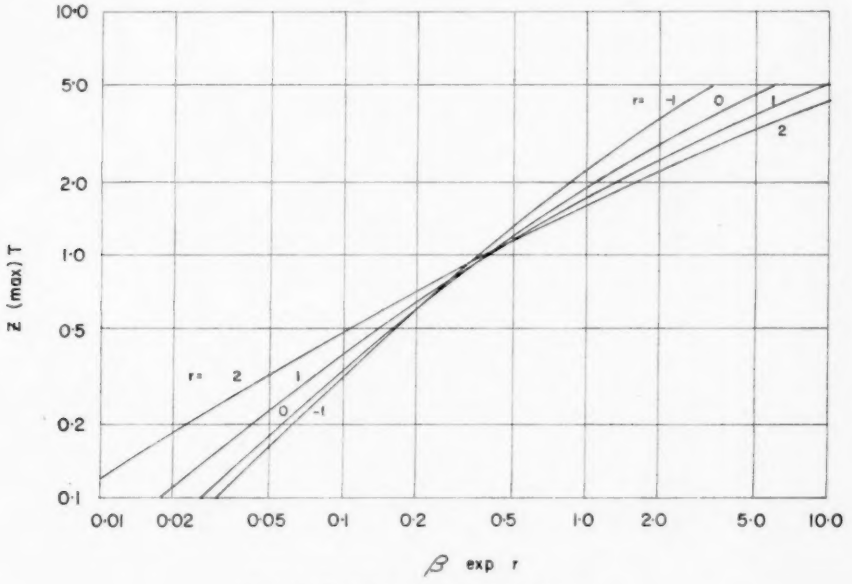

FIG. 1. $Z_{\max}T$ as a function of β exp r.

The value of the material parameter β can be obtained from the measured values of α, σ and κ for any specimen of the material of essentially extrinsic electrical conductivity in the following manner: If A_a and K_a are the values of $(e/k) \mid \alpha \mid$ and $(e/k)^2\kappa/\sigma T$, respectively, for that specimen, then

$$\beta^{-1} = [F_r(\eta_a)/r!]\, [K_a - L(r, \eta_a)] \tag{9}$$

from equation (7) and also

$$A_a = \frac{r + 2}{r + 1}\frac{F_{r+1}(\eta_a)}{F_r(\eta_a)} - \eta_a \tag{10}$$

from equation (3), where η_a is the value of the reduced Fermi energy for the specimen. Elimination of η_a between equations (9) and (10) gives β as a function of K_a, A_a and r. This functional relationship is computed conveniently by assuming various values of η_a and K_a and computing β and A_a. Since $Z_{\max}T$ is a function of β and r, $Z_{\max}T$ may be expressed as a function of A_a, K_a, and r.

The combinations of values of A_a and K_a that correspond to a given value of $Z_{\max}T$ were computed with the aid of a high-speed digital computer for small increments in A_a

from $A_a = 0$ up to the value of A_a required to obtain K_a at least equal to 1000. These computations were made for various values of $Z_{max}T$ ranging from 0·05 to 5·0 in approximately 20 per cent intervals in $Z_{max}T$ and for each of the four cases of $r = -1$, 0, 1, and 2, respectively.

The solid lines of Fig. 2 show some representative results of these computations, the curves of $Z_{max}T = 0{\cdot}25$, 0·5, 1·0, and 2·0 for $r = -1$, 0, 1, and 2. $\kappa/\sigma T = (k/e)^2 K_a$ is represented on a logarithmic scale along the ordinate and $|\alpha| = (k/e) A_a$ is represented on a linear scale along the abccissa.

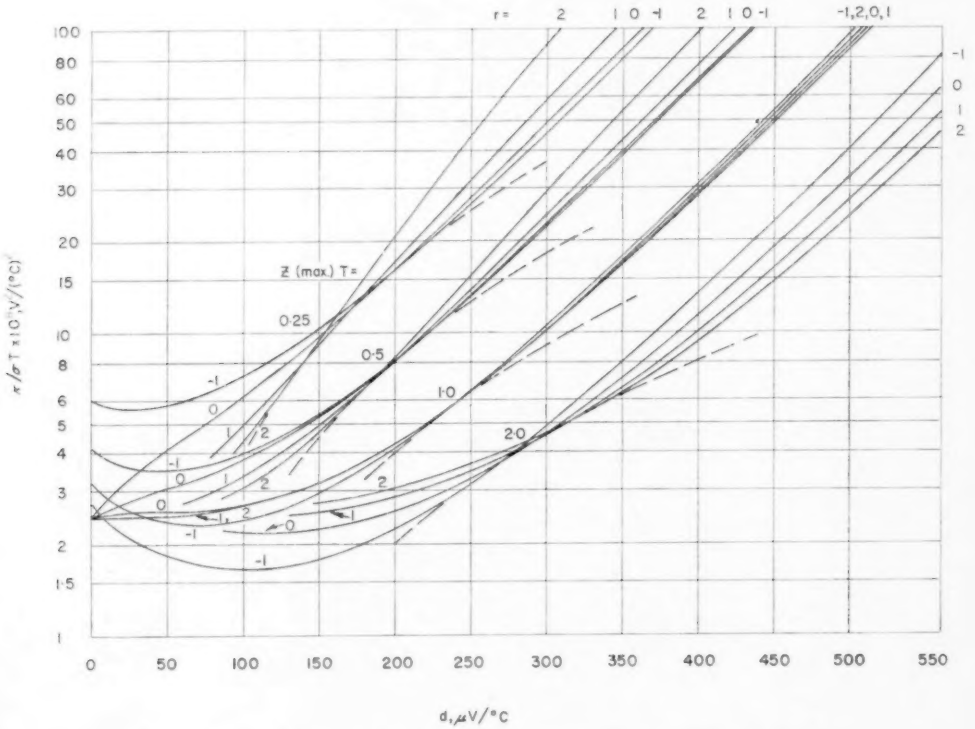

FIG. 2. $Z_{max}T$ and $Z_{meas}T$ as functions of r and measured values of α and $\kappa/\sigma T$.

The broken lines of Fig. 2 connect constant values of $Z_{meas}T = A_a^2/K_a = \alpha^2\sigma T/\kappa = 0{\cdot}25$ through 2·0. Optimized materials are those with ($\kappa/\sigma T$, $|\alpha|$) combinations that fall in the region of tangency of the $Z_{max}T$ and $Z_{meas}T$ curves.

DISCUSSION

It is to be noted from Fig. 2 that the relationship among $Z_{max}T$, $\kappa/\sigma T$ and α is essentially independent of r in the vicinity of $Z_{max}T = 1{\cdot}0$. This relationship is also relatively insensitive to r for optimized materials, and becomes somewhat more sensitive to r for underdoped materials (those with $\kappa/\sigma T$ and α combinations that fall above and to the right of the region of optimized materials). Lack of knowledge concerning the value of r

does not preclude the attainment of a useful degree of approximation of $Z_{max}T$ in the region of underdoping for $Z_{max}T$ ranging from about 0·25 to about 2·0.

The relationship among $Z_{max}T$, $\kappa/\sigma T$, and α becomes more critically dependent upon r as the doping is increased above its optimum value. The curves for the various values of r for a given value of $Z_{max}T$ can be seen to spread out rapidly and intersect those for neighboring values of $Z_{max}T$ in this region. It is important to have fairly accurate information as to the effective value of r in this region if useably accurate estimates of $Z_{max}T$ are to be obtained.*

As the doping is still further increased, all of the $Z_{max}T$ curves for $r = 0$, 1, and 2 converge toward the point $\alpha = 0$, $\kappa/\sigma T = (k/e)^2 (\pi^2/3) = 2{\cdot}44 \times 10^{-8}$ (V/deg)^2, the limiting values of the Seebeck coefficient and the Lorentz number, respectively, for high degeneracy. (Some of the $Z_{max}T$ curves on Fig. 2 are terminated before reaching this point of convergence in order to avoid confusion.) For $r = -1$, the limiting value of $\kappa/\sigma T$ is $(k/e)^2 (\beta^{-1} + \pi^2/3)$, since σ approaches the finite value of σ_0 for $r = -1$ as the carrier concentration increases. However, the continuation of the $r = -1$ curves to $\alpha = 0$ has no physical significance, since impurity scattering must eventually result in increasing r above -1 as the doping level is increased. The curves of Fig. 2 would have no practical utility for determining $Z_{max}T$ if the measured values of α and $\kappa/\sigma T$ for a given specimen plot near the point of convergence.

The accuracy of the estimation of $Z_{max}T$ from the values of A_a and K_a for greatly overdoped materials is poor because κ_{ph} is essentially masked by the much larger electronic contribution to the thermal conductivity for such materials. κ_{ph} appears as a factor in the definition of the material parameter β. Thus, as η_a increases, $F_r(\eta_a)/r!$ increases indefinitely for $r > -1$, the value of K_a approaches $L(r, \eta_a)$, and the reciprocal of the constant material parameter β^{-1} as obtained from equation (9) involves the product of an increasingly large number and a decreasingly small difference between two almost equal numbers. Furthermore, since $\partial A_a/\partial \eta_a$ approaches zero rapidly with increase in η_a for positive values of η_a, the determination of the value of η_a from the measured value of A_a with the aid of equation (10) becomes less accurate as η_a increases.

The use of Fig. 2 simplifies the analysis of thermoelectric materials. It is not necessary to obtain explicit values for such quantities as r, μ_c, κ_{ph}, m nor for the carrier concentration. The numerical value of the dimensionless parameter $\beta \exp r$ can be obtained directly from Fig. 1, if desired, using the value of $Z_{max}T$ obtained from Fig. 2.

EFFECTS OF DEVIATIONS FROM BASIC ASSUMPTIONS

The above analysis applies only to the case where the electronic transport is essentially by means of a single type of charge carrier in a single conduction band and for which neither β nor r changes with the concentration of doping agent.

The curves of Fig. 2 were obtained by numerical computation, using Fermi-Dirac statistics, in the manner outlined above. However, in order to assess the effects of deviations from the basic assumptions conveniently, it would be desirable to formulate an approximate analytical expression for those portions of the curves at and above the region of $Z_{max}T = Z_{meas}T$. Such an expression is readily obtained by using the classical-statistics

* It is tacitly assumed in this discussion that the scattering mechanism can be characterized by a simple power law relationship between mean free path and energy in this region, although mixed scattering is more likely to occur. The effects of mixed scattering on the $Z_{max}T$ analysis is discussed later.

approximations for the various Fermi integrals that appear in equations (9) and (10). The approximations are only fair ones in the neighborhood of $Z_{max}T = Z_{meas}T$, since values of η_0 are in the range of about -2 to about $+2$ for the range of values of $Z_{max}T$ and r shown on Fig. 2. However, the approximations improve as A_a and K_a increase (decreasing η_a). We thus have $F_r(\eta_a)/r! \to \exp \eta_a$, $L(r, \eta_a) \to r + 2$ and $A_a \to r + 2 - \eta_a$. Elimination of η_a between the classical-statistics forms of equations (9) and (10) results in

$$\ln [K_a - (r + 2)] - A_a = -\ln \beta - (r + 2). \tag{11}$$

Since $Z_{max}T$ is a function of β and r, curves of constant $Z_{max}T$ on Fig. 2 in the region of interest should correspond to curves of $\ln [K_a - (r + 2)] - A_a = \text{constant}$. This may be shown to be a fairly good representation of the actual curves in the region of interest. (For $K_a \gg r + 2$, the curves reduce to straight lines of unit slope on a plot of $\ln K_a$ versus A_a, as is evident from Fig. 2 for $K_a >$ about 50.) Equation (11) also indicates why $Z_{max}T$ is a function primarily of the combination $\beta \exp r$ of the two material parameters r and β, as previously noted. Joffé [1] showed that $Z_{max}T = 4\beta \exp r$ at $\eta_0 = r$ by assuming that classical statistics applies to optimized materials and also that the thermal conductivity is essentially entirely κ_{ph}. Neither one of these assumptions is a good approximation for thermoelectric materials of present interest.

The effects of departures from the underlying assumptions will be evaluated in terms of the resultant deviations from the invariance of the quantity $\ln [K_a - (r + 2)] - A_a$.

Minority-carrier effects

When following a curve of $Z_{max}T = \text{constant}$ on Fig. 2 in the direction of decreasing carrier concentration (increasing K_a and A_a) the relative concentration of minority carriers to that of the majority carriers increases and must eventually become great enough to affect the accuracy of the estimate of $Z_{max}T$ by an appreciable amount.

If the subscript a continues to refer to quantities associated with the majority carrier, the subscript m to those of the minority carrier, and the subscript t to resultant quantities, we have

$$A_t = \frac{\sigma_a}{\sigma_t}(r_a + 2 - \eta_a) - \frac{\sigma_m}{\sigma_t}(r_m + 2 - \eta_m) \tag{12}$$

and

$$K_t = \left(\frac{e}{k}\right)^2 \frac{\kappa_t}{\sigma_t T} = \left(\frac{e}{k}\right)^2 \frac{\kappa_{ph}}{\sigma_t T} + (r_a + 2)\frac{\sigma_a}{\sigma_t} + (r_m + 2)\frac{\sigma_m}{\sigma_t} + (r_a + r_m + 4 + \eta_G)^2 \frac{\sigma_a \sigma_m}{\sigma_t^2}, \tag{13}$$

where η_G is the width of the energy gap between the conduction and valence bands in units of kT. The last term in equation (13) arises from the ambipolar diffusion contribution to κ_t [3].

For $\sigma_m/\sigma_a \ll 1$, we have $\sigma_a/\sigma_t = 1 - \sigma_m/\sigma_a$ and $\sigma_m/\sigma_t = \sigma_m/\sigma_a$ to first-order approximations. Equation (12) becomes

$$A_t = A_a - (r_a + r_m + 4 + \eta_G)(\sigma_m/\sigma_a), \tag{14}$$

since $\eta_G = -(\eta_a + \eta_m)$. Likewise, equation (13) becomes

$$K_t = K_a + [(r_a + r_m + 4 + \eta_G)^2 + (r_m + 2) - K_a](\sigma_m/\sigma_a). \tag{15}$$

Finally, the difference between $\ln [K_i - (r_a + 2)] - A_i$ and $\ln [K_a - (r_a + 2)] - A_a$ is

$$\Delta\{\ln [K_a - (r + 2)] - A_a\} = \left[r_a + r_m + 3 + \eta_G + \frac{(r_a + r_m + 4 + \eta_G)^2 + (r_m - r_a)}{K_a - (r_a + 2)}\right] \frac{\sigma_m}{\sigma_a} \quad (16)$$

to the first order in the ratio σ_m/σ_a. Since the coefficient of σ_m/σ_a in equation (16) is positive, even for both r_a and r_m possibly as low as -1, the effect of the minority carriers is to increase the measured value of $\ln [K - (r + 2)] - A$, and thus, as can be seen from Fig. 2, to give an indicated value of $Z_{\max}T$ which is smaller than the actual value characteristic of strictly extrinsic material.

Equation (16) indicates that the change in the indicated value of $Z_{\max}T$ resulting from the presence of minority carriers depends upon σ_m/σ_a rather than on the relative concentrations of the two carriers. The $Z_{\max}T$ analysis should thus be applicable even to intrinsic material if the mobility of one carrier were much greater than that of the other. These conclusions require more careful consideration in view of the fact that η_G and σ_m/σ_a are not independent quantities.

The value of η_G for a given material at a given temperature is a constant. The minority carrier concentration n_m is then determined by that of the majority carrier n_a, since the relationship $n_m n_a = N_m N_a \exp(-\eta_G)$ must be satisfied, where $N_m = 2(2\pi m_m \mathscr{k}T/h^2)^{3/2}$ and $N_a = 2(2\pi m_a \mathscr{k}T/h^2)^{3/2}$. Hence, $\sigma_m\sigma_a = \sigma_{0m}\sigma_{0a}\exp(-\eta_G)$, where $\sigma_{0m} = N_m e\mu_{cm}$ and $\sigma_{0a} = N_a e\mu_{ca}$. Finally, dividing by σ_a^2, we have

$$\sigma_m/\sigma_a = (\sigma_{0m}/\sigma_{0a})\exp(-\eta_G - 2\eta_a), \quad (17)$$

where the classical approximation $\sigma_a = \sigma_{0a}\exp\eta_a$ is made. Hence, for a given value of η_G, the value of σ_m/σ_a is determined by the values of $\sigma_{0m}/\sigma_{0a} = (m_m/m_a)^{3/2}(\mu_m/\mu_a)$ and by the reduced Fermi energy η_a. The latter is directly related by the relationship $A_a = r + 2 - \eta_a$ to the particular point on the pertinent curve of $Z_{\max}T =$ constant at which it is desired to compute the change in indicated $Z_{\max}T$.

The results of some illustrative numerical computations are given in Table 1 for $\sigma_{0m} = \sigma_{0a}$, for $r_a = r_m = 0$ (charge carrier scattering by lattice vibrations), and for combinations of values of A_a and K_a that represent points on the curve $Z_{\max}T = 1{\cdot}0$. The tabulated values of $\Delta \ln [Z_{\max}T]$ are $-2/3$ of the values of $\Delta\{\ln [K_a - (r_a + 2)] - A_a\}$ obtained from equation (16); this relationship is a good approximation in the neighborhood of $Z_{\max}T = 1$.

It is to be noted from Table 1 that, for the case of $\sigma_{0m} = \sigma_{0a}$, σ_m/σ_a must not exceed about 2/3 of 1 per cent (e^{-5}) for the indicated value of $Z_{\max}T$ to be no more than about 10 per cent lower than the value of $Z_{\max}T$ for strictly extrinsic material. For nearly optimized material ($A_a = 3$, $K_a = 9$),* this lower limit on σ_m/σ_a is seen in Table 1 to correspond to an energy gap of $7\mathscr{k}T$ (0·18 eV at room temperature).

For underdoped materials, the minimum value of η_G required to obtain a given value of σ_m/σ_a, and hence approximately a given constant error in the indicated value of $Z_{\max}T$, increases with decrease in doping level (increasing A_a and K_a), as can be seen in Table 1.

For values of σ_{0m}/σ_{0a} other than unity, both the first column and the last column in Table 1 must be multiplied by the value of σ_{0m}/σ_{0a}. For $\sigma_{0m}/\sigma_{0a} = 0{\cdot}2$, for example,

* Exactly optimized material for $Z_{\max}T = 1$ would correspond more closely to $A_a = 2{\cdot}80$, $K_a = 7{\cdot}84$.

σ_m/σ_a cannot exceed about $0{\cdot}2e^{-3} = 1$ per cent for about a 10 per cent or smaller magnitude of error in $Z_{\max}T$ and the required values of η_G are smaller by 2 units for each (A_a, K_a) combination than for the case of $\sigma_{0m}/\sigma_{0a} = 1$. If σ_{0m}/σ_{0a} is greater than unity, smaller values of σ_m/σ_a and greater values of η_G are required for $\Delta Z_{\max}T \leqslant 10$ per cent.

TABLE 1. EFFECT OF MINORITY CARRIERS ON THE INDICATED VALUE OF $Z_{\max}T$ FOR $Z_{\max}T \approx 1{\cdot}0$

σ_m/σ_a	A_a	K_a	η_G	$\Delta \ln [Z_{\max}T]$
$e^{-2} = 0{\cdot}135$	3	9	4	$-1{\cdot}45$
	4	20	6	$-1{\cdot}31$
	5	50	8	$-1{\cdot}25$
	6	140	10	$-1{\cdot}30$
$e^{-3} = 0{\cdot}050$	3	9	5	$-0{\cdot}65$
	4	20	7	$-0{\cdot}56$
	5	50	9	$-0{\cdot}51$
	6	140	11	$-0{\cdot}52$
$e^{-4} = 0{\cdot}0183$	3	9	6	$-0{\cdot}28$
	4	20	8	$-0{\cdot}23$
	5	50	10	$-0{\cdot}21$
	6	140	12	$-0{\cdot}21$
$e^{-5} = 0{\cdot}0067$	3	9	7	$-0{\cdot}12$
	4	20	9	$-0{\cdot}10$
	5	50	11	$-0{\cdot}08$
	6	140	13	$-0{\cdot}08$
$e^{-6} = 0{\cdot}00025$	3	9	8	$-0{\cdot}05$
	4	20	10	$-0{\cdot}04$
	5	50	12	$-0{\cdot}03$
	6	140	14	$-0{\cdot}03$

Since σ_m/σ_a must be of the order of 1 per cent or less for the $Z_{\max}T$ analysis to be about 10 per cent or less in error, a mobility ratio, μ_{ca}/μ_{cm}, of the order of magnitude of 100 or greater would be required for the analysis to be applicable to intrinsic materials with reasonable accuracy. The relationship between σ_{0a}/σ_{0m} and μ_{cm}/μ_{ca} would depend upon how the mobility varies with the effective mass, as determined by the scattering mechanism involved.

Impurity-scattering effects

As the concentration of doping agent is increased, the scattering of charge carriers on the ionized impurity centers becomes an increasing fraction of the total scattering, and the assumption that β and r are independent of doping level is eventually no longer a good approximation. β would decrease because of the resultant reduction in the mobility of the charge carriers but r would effectively increase, since scattering by impurity centers entails a stronger variation of the mean free path of the charge carrier with its kinetic energy than does scattering by lattice vibrations.

Since $\{\Delta \ln [K_a - (r + 2)] - A_a\} = \Delta \ln (\kappa_{ph}/\sigma_a T) - \Delta A_a = \Delta \ln \rho_a - \Delta A_a$, if κ_{ph} is constant, the effects of the addition of impurity scattering on the indicated value of $Z_{\max}T$

may be evaluated by computing the resultant change in the value of $\ln \rho_a - A_a$, assuming that no appreciable scattering of phonons takes place on the impurity centers.

Johnson and Lark-Horowitz computed the effects of various amounts of impurity scattering on the electrical resistivity [4]. They found that the resultant resistivity ρ_t is given by $\rho_t = (\rho_l + \rho_i)/\Gamma$, where ρ_l is the resistivity with lattice scattering alone ($r_l = 0$), and ρ_i would be the resistivity if all the scattering were on the ionized impurities ($r_i = 2$). Γ is a function of $\rho_i/(\rho_i + \rho_l)$ that equals unity for $\rho_i/(\rho_i + \rho_l) = 0$ or 1 and has a shallow minimum at $\rho_i/(\rho_i + \rho_l) =$ about 1/2. Hence, $\Delta \ln \rho_a = \ln (\rho_t/\rho_l) = \ln [(\rho_l + \rho_i)/\rho_l\Gamma]$.

Johnson and Lark-Horowitz [5] also computed the value of the Seebeck coefficient for various proportions of mixed scattering with $r_l = 0$ and $r_i = 2$. Their results may be expressed in the form $A_a = 2 + r_t - \eta_a$, where r_t is a function of $\rho_i/(\rho_i + \rho_l)$.

Since $\Delta A_a = \Delta r$,

$$\Delta \ln \rho_a - \Delta A_a = \ln [(\rho_l + \rho_i)/\rho_l\Gamma] - \Delta r \qquad (17)$$

Table 2 lists the results of computations of $\ln [(\rho_l + \rho_i)/\rho_l\Gamma] - \Delta r$ for various values of $\rho_i/(\rho_l + \rho_i)$. The third column of Table 1 lists the approximate change in the indicated value of $Z_{max}T$ in the neighborhood of $Z_{max}T = 1$. The change in the indicated value of $Z_{max}T$ would rise to a maximum positive value for some value of $\rho_i/(\rho_l + \rho_i) \leqslant 0{\cdot}1$, since $\Delta Z_{max}T = 0$ for $\rho_i = 0$. It is noteworthy that the indicated value of $Z_{max}T$ is less than about 10 per cent in error even if impurity scattering accounts for as much as half of the total electrical resistivity.

TABLE 2. EFFECT OF IMPURITY SCATTERING ON THE INDICATED VALUE OF $Z_{MAX}T$ FOR $Z_{MAX}T \approx 1$

$\rho_i/(\rho_i + \rho_l)$	$\Delta \ln \rho_a - \Delta A_a$	$\Delta \ln [Z_{MAX}T]$
0·1	0·329−0·379 = −0·050	+0·03
0·2	0·525−0·558 = −0·033	−0·02
0·3	0·700−0·698 = +0·002	0
0·4	0·868−0·809 = +0·059	−0·04
0·5	1·050−0·947 = +0·103	−0·07
0·6	1·245−1·065 = +0·180	−0·12

If impurity-scattering effects begin to become appreciable at doping concentrations that are approximately optimum, the indicated changes in $Z_{max}T$ represent actual changes in this quantity. The effect of impurity scattering on the maximum figure of merit was investigated by Ure [6] with similar conclusions; i.e. although small amounts of impurity scattering may result in up to a few per cent increase in $Z_{max}T$, larger amounts would be deleterious.

Mixed scattering with combinations of other values of r than 0 and 2 are also possible, such as may result from some degree of ionicity in the lattice or from scattering on neutral impurities. The effects on the indicated values of $Z_{max}T$ of changes in β and r with doping level resulting from other scattering mechanisms remain to be investigated.

Multiband-conduction effects

The situation is more complicated if extrinsic electrical conduction in more than one band is involved (such as in an impurity band in addition to the conduction or valence band or in more than one nonequivalent minimum of the conduction band or maximum in the

valence band), since different values of β and r may be associated with each such band or extremum. Changing the carrier concentration by altering the doping may involve also changing the distribution of carriers among the different conduction bands or extrema. Under such circumstances, the set of points plotted on Fig. 2 that represent the combinations of measured values of α and $\kappa/\sigma T$ for various amounts of doping may not fall on a curve of $Z_{max}T =$ constant. A more complex analysis would be needed to obtain $Z_{max}T$ for such materials. However, if optimized material involves conduction predominantly in a single band, the theory developed herein might still be applicable to a useful degree of approximation for carrier concentrations in the neighborhood of the optimum one. It may be possible to develop first-order corrections for small relative conductivities in the other bands in a manner similar to that developed above for evaluating the effects of a small relative conductivity of a minority carrier.

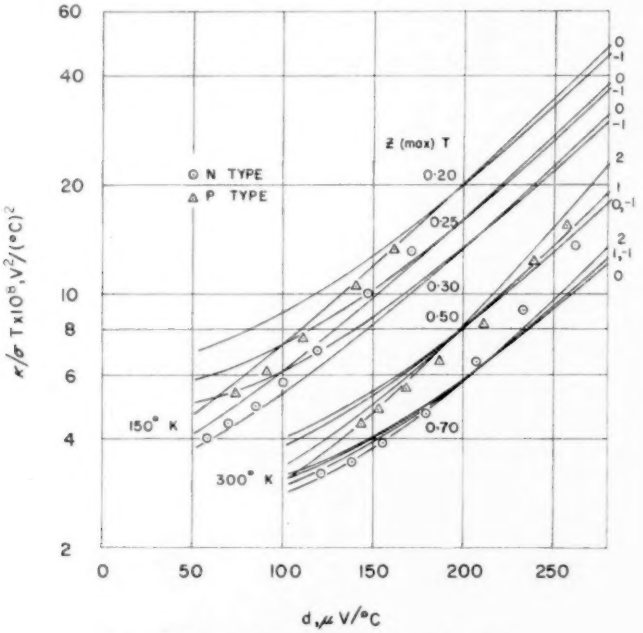

FIG. 3. $Z_{max}T$ plot of Goldsmid's Bi_2Te_3 data.

EXPERIMENTAL EVIDENCE

The circles and triangles on Fig. 3 represent values of α and $\kappa/\sigma T$ obtained from Goldsmid's experimental curves of the variations of α, κ and σ of halogen-doped n-type and of p-type Bi_2Te_3, respectively, as the concentrations of doping agents are changed [7, 8]. The two sets of points are for the same materials at two different temperatures, 150°K and 300°K. The theoretical curves of $Z_{max}T = 0{\cdot}20, 0{\cdot}25, 0{\cdot}30, 0{\cdot}50$, and $0{\cdot}70$ are also shown, with the curves for $r = 1$ and 2 for the first three values of $Z_{max}T$ omitted for the sake of clarity.

All of the 150°K points for both the p-type and the n-type specimens lie below the region of optimum doping, indicating that all of the specimens are overdoped at this temperature. The sets of points for both the p-type and the n-type specimens lie approximately parallel to the $Z_{max}T =$ constant curves for $r = 0$. This is in reasonable agreement

with Goldsmid's observations from the temperature variation of the electrical conductivities of the various specimens that r = about $-0{\cdot}2$ for electron conduction and about $-0{\cdot}4$ for hole conduction in Bi_2Te_3. For the lowest lying triangle and circle at 150°K, the indicated values of $Z_{max}T$ are about 0·22 and 0·29, respectively, whereas the actual values of $Z_{meas}T$ for these specimens are 0·10 and 0·08, respectively. For the highest lying triangle and circle the indicated values of $Z_{max}T$ are about 0·20 and 0·23 respectively, and the actual values of $Z_{meas}T$ are 0·20 and 0·22, respectively. Hence, these uppermost points are overdoped by inappreciable amounts; they fall just below the region of optimum doping.

It is thus seen that a good estimate of $Z_{max}T$ can be obtained from any single specimen at 150°K, if some information is available as to the approximate value of r, despite the fact that the specimens are all overdoped at this temperature. It is seen from Fig. 2, however, that the estimate of $Z_{meas}T$ would become increasingly more difficult to make for specimens doped to obtain values of the Seebeck coefficient less than about 50 μV/deg.

The increase in the indicated value of $Z_{max}T$ with increasing doping level is probably the result of an increasing amount of impurity scattering, as previously discussed. No observable intrinsic conduction effects are to be expected for any of the points on the 150°K curves. A decrease of 10 per cent in the indicated value of $Z_{max}T$ for the uppermost points would require a value of η_G of about 5, whereas η_G = about 12 for Bi_2Te_3 at 150°K.

The points for 300°K for both the p-type and the n-type specimens straddle the region of optimum doping. The five lowermost triangles lie reasonably parallel to $Z_{max}T$ = constant for $r = 0$ and indicate a value of $Z_{max}T$ of about 0·55. The actual values of $Z_{meas}T$ for the two uppermost triangles of this set of five are both 0·54, indicating that these two are about optimum-doped. The two triangles in the region of underdoping indicate decreased values of $Z_{max}T$ probably because of minority carrier effects. A value of η_G of about 7 would be required to obtain a 10 per cent decrease in indicated $Z_{max}T$ in the region of these two uppermost points, and the value of η_G for Bi_2Te_3 at 300°K is about 6.

For the n-type materials at 300°K, the lowermost four points indicate that $Z_{max}T$ = about 0·72. However, for the n-type material, minority carriers begin to become effective in reducing the indicated $Z_{max}T$ to about 0·67 at about the region of optimum doping (fifth circle from the bottom). The value of $Z_{meas}T$ for this specimen is also 0·67. The uppermost two circles indicate appreciably large decreases in $Z_{max}T$. Significant contributions to κ from ambipolar diffusion effects are indicated for these specimens from their positions on Goldsmid's curve of κ versus σ.

The $Z_{max}T$ analysis developed herein would thus seem to be suitable for Bi_2Te_3 despite the inapplicability of the assumption of spherical constant-energy surfaces for this material. The extension of this analysis to include materials with non-spherical constant-energy surfaces and possibly also a multiplicity of equivalent minima in the conduction band or maxima in the valence band may involve essentially only a more general definition of β to incorporate the number of such extrema and the anisotropies in m, μ_e, and κ_{ph}. In the general case β would thus be a function of crystallographic direction.

CONCLUSIONS

1. An estimate of $Z_{max}T$ for a thermoelectric material can be obtained from the measured values of the Seebeck coefficient, electrical conductivity, and thermal conductivity of a single specimen of the material with essentially extrinsic electrical conductivity. An estimate can also be obtained of the change in doping that would be required to produce optimized material if the measured specimen is not already optimized.

2. The estimate of $Z_{max}T$ is a particularly good one for specimens that are already approximately optimized. For underdoped specimens it is necessary to ascertain that the value of the energy gap in kT units is great enough to avoid any appreciable error in the indicated value of $Z_{max}T$ from minority carrier effects. If the value of the energy gap is not known, it would be advisable to prepare a second specimen with a carrier concentration closer to optimum, of possible, and to compare the indicated values of $Z_{max}T$ for the two specimens. If the two indicated values of $Z_{max}T$ are distinctly different, measurements on a third specimen with still greater carrier concentration are desirable.

3. If it is possible that more than about half of the electrical resistivity of a specimen is the result of scattering of the charge carriers on ionized impurities, because of excessive overdoping and/or low temperature, the indicated value of $Z_{max}T$ may be substantially in error. Measurements on one or more additional specimens with different doping concentrations would then be desirable.

4. The value of the scattering parameter r is not needed for applying this analysis to materials with $Z_{max}T$ values in the neighborhood of unity. For materials with $Z_{max}T \leqslant$ about $0{\cdot}5$, an estimate of the value of r is needed in order to obtain a reasonably accurate value of $Z_{max}T$, particularly for somewhat overdoped materials. For materials that may be developed in the future with $Z_{max}T \geqslant$ about $2{\cdot}0$, an estimate of r would also be required to obtain reasonably accurate values of $Z_{max}T$.

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NOTE ADDED IN PROOF

The general theory for multiband conduction of both electrons and holes has been developed and is being prepared for publication.

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NEW EXPERIMENTS ON INTERACTION OF PHONONS WITH CRYSTALLINE DEFECTS*

KURT HUBNER† and W. SHOCKLEY‡

Summary—Transmitted phonon drag has been used to observe the scattering of phonons by dislocations and precipitates in single crystal silicon at liquid nitrogen temperature.

A SIMPLE theory of the transmitted phonon drag [1], its first experimental observation [2] and its application to the study of phonon-hole and phonon–phonon scattering [3] have been published elsewhere.

As in the experiments reported earlier, all samples investigated were symmetrical, diffused *npn* structures, with the junctions in the (100) plane at a depth x_j measured from the surfaces. The major impurity in the outer layers was phosphorus with a surface concentration n_s and boron of concentration p for the middle layer of thickness W_p.

The transmitted phonon drag is observed by applying an electric field E_1 along the first n-layer parallel to the p–n junctions. This causes an electron current and, through lattice scattering, a coherent flow of those "relevant" phonons which interact with electrons. Some of these phonons reach the second n-layer and through phonon drag set up a field E_2 of opposite polarity.

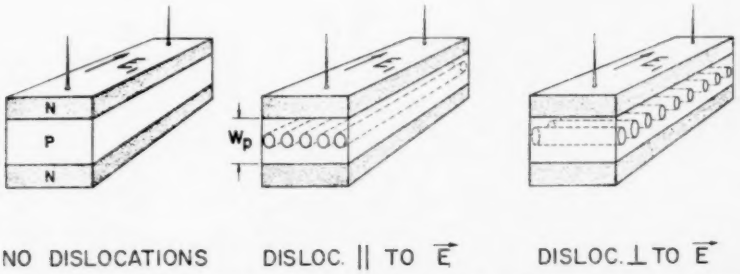

FIG. 1. Orientation of edge dislocations in the samples. The bulk impurity concentration is $p = 1{\cdot}4 \times 10^{15}\,\mathrm{cm}^{-3}$ boron; the surface concentration of the diffused outer layers is $n_s = 4{\cdot}5 \times 10^{17}\,\mathrm{cm}^{-3}$ phosphorus; and the junction depth x_j is 15 μ.

The transmission of these phonons through the middle p-layer can be studied by recording E_2/E_1 versus W_p or other parameters. This then yields information on the decay of the phonon drift momentum in the middle p-layer. In the experiments reported here, this decay arises mainly from phonon–phonon scattering and from defects deliberately introduced into the intermediate p-layer.

The effect of dislocations was investigated on samples cut from a crystal containing a $10{\cdot}25° \pm 0{\cdot}5°$ grain boundary in a (100) plane with the edge dislocations running in the (001) direction. This direction for the two grains coincided within $\pm 0{\cdot}5°$, as determined by

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† In partial fulfillment of Ph.D. requirements.
‡ Shockley Transistor, Unit of Clevite Transistor, Palo Alto, California.

X-rays. Samples were cut so that the plane of the grain boundary was parallel to the p–n junctions and contained in the intermediate p-layer. Measurements of E_2/E_1 were taken on two sets of samples having a W_p of 223 μ and 300 μ for two orientations of the dislocations with respect to the direction of the electric fields, and on control samples which did not contain a grain boundary, as indicated in Fig. 1. The results are shown in Table 1 in which E_2/E_1 is given for every sample measured, together with the averaged attenuation in percentage over the control sample.

It is seen that when the dislocations are perpendicular to the electric fields a much more pronounced attenuation is observed than when they are parallel to the fields. For the low boron concentration of $p = 1{\cdot}4 \times 10^{15}$ cm^{-3}, phonon–phonon scattering is probably the dominant scattering mechanism. As the phonon mean free path for this type of scattering goes with the inverse of the wave number squared for low frequency longitudinal acoustical phonons [4], the important phonons for a large W_p are of lower frequency than those for a small W_p. If one dares to draw conclusions from the relatively small differences of the attenuations for $W_p = 223$ μ and $W_p = 300$ μ, it would follow that the scattering cross-section of the dislocations goes with the phonon wave length to a positive power.

TABLE 1. VALUES OF $|E_2/E_1|$ MEASURED ON SAMPLES CONTAINING A LOW-ANGLE GRAIN BOUNDARY IN THE INTERMEDIATE p-LAYER (as shown in Fig. 1)

$W_p(\mu)$	No dislocations	Dislocations	
		Parallel to **E**	Perpendicular to **E**
223	$9{\cdot}0\times10^{-5}$ 10·0	$8{\cdot}7\times10^{-5}$ 8·4	$4{\cdot}7\times10^{-5}$ 6·1 6·6
		−10%	−39%
300	$6{\cdot}4\times10^{-5}$ 6·2	$5{\cdot}4\times10^{-5}$ 5·0	$3{\cdot}6\times10^{-5}$ 3·3
		−17%	−45%

The encouraging small scatter and reproducibility of the experiments on dislocations led to an investigation of the influence of oxygen precipitates on the phonon transmission. It is well known that silicon pulled from the melt, such as was used here, contains a high concentration of oxygen due to the contact with the quartz crucible. Precipitation of this oxygen upon heat treatment has been investigated by Kaiser [5] and others. For a heat treatment of 50 hr at 1000°C, Kaiser found by optical means that the average diameter of the precipitates was 1000 Å. Rapid cooling of the samples from the diffusion temperature of 1300°C to room temperature in about 15 sec should yield much smaller precipitates.

The spectrum of the relevant phonons at liquid nitrogen temperature centers around a wavelength of about 100 Å and is limited on the low side by the energy of the electrons and on the high side by the physical dimensions of the crystal.

The diameters of the precipitates are therefore of the same order of magnitude as the phonon wavelengths. The above mentioned sorting mechanism due to phonon–phonon scattering should reveal phonon-precipitate scattering on a plot of E_2/E_1 versus W_p, with

small precipitates reducing E_2/E_1 values at small W_p, and big ones at large W_p. This behavior has actually been observed and the results are shown in Fig. 2, where E_2/E_1 versus W_p is plotted for two sets of samples, differing only in an additional heat treatment given to one set. The parameters of the samples are given in the figure. There is a distinct attenuation of E_2/E_1 for the heat treated samples around $W_p = 500\ \mu$, while the rapidly cooled samples yield lower values for E_2/E_1 at small W_p.

Experiments like these reported here seem to indicate that the transmitted phonon drag is a powerful tool in investigating all kinds of processes involving phonons.

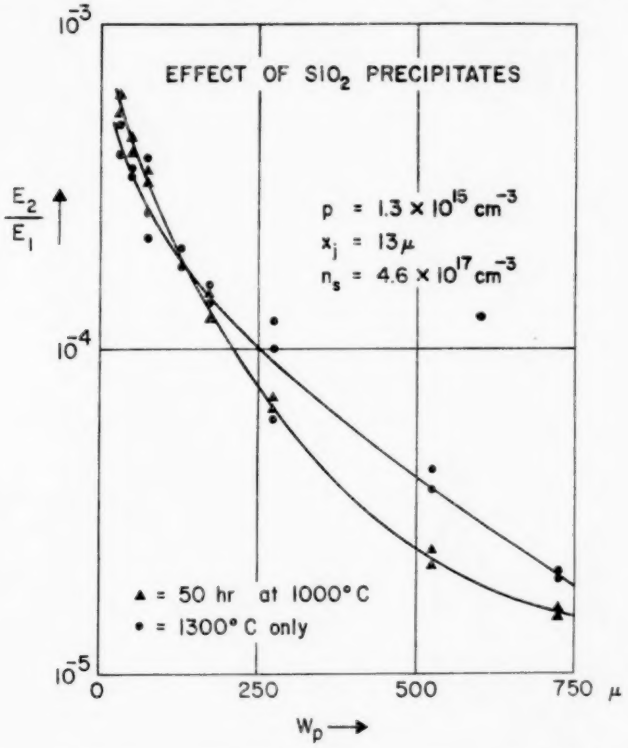

FIG. 2. Measurement of the transmitted phonon drag on samples containing two sizes of SiO_2 precipitates.

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THERMOELECTRIC EQUIVALENT CIRCUITS

WILLIAM H. HARTWIG*

ABSTRACT

ANALYSIS of transistor circuits contributed much to the early acceptance of these devices by circuit designers. Thermoelectric circuits can be similarly represented starting with the entropy equation and Onsager's reciprocal relations. The flow quantities of current and heat and potential quantities of voltage and temperature can be interrelated using two simultaneous equations similar in form to those written for four terminal networks of all kinds.

This paper derives several equivalent circuits and defines sets of admittance and impedance parameters. The Onsager coefficients are written in terms of physical parameters such as the electrical and thermal conductance, the Peltier coefficient and Seebeck voltage.

Two generator equivalent circuits are presented. The parameters can be treated as constants which permit simple expressions for power and efficiency. The equations become non-linear if temperature dependence of the parameters is included.

The effects of contact losses and heat storage are introduced with equivalent resistances and capacitors. Transient behavior is examined as a circuit problem with equivalent time-constants derived for simple cases.

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ANISOTROPY OF THE SEEBECK COEFFICIENTS OF BISMUTH TELLURIDE

JANE H. DENNIS*

Summary—Anisotropy in the Seebeck effect is found to arise in two separate theoretical situations. It will arise in a single-carrier system when there are two competing scattering mechanisms. One of these (lattice scattering, for example) must be isotropic.

The anisotropy will arise in a two-carrier system when there is only a single scattering mechanism. In this case, the anisotropy arises because the conduction and valence band structures are not identical; hence the ratio of the mobility of holes to the mobility of electrons is different in the two principal crystallographic directions.

The single-carrier, multiple-scattering theory of the anisotropy is confirmed experimentally on *n*-type iodine-doped Bi_2Te_3 at low temperatures (100–300°K). The multiple-carrier, single-scattering theory is confirmed on stoichiometric undoped Bi_2Te_3 at high temperatures (300–700°K), when mixed conduction has set in and lattice scattering predominates.

INTRODUCTION

MATERIALS with anisotropic crystal structures may in general be expected to have anisotropic electrical and thermal conductivities. However, the Seebeck coefficient tensor will be anisotropic only under two rather special conditions. One way to make the Seebeck effect anisotropic is to cause two scattering mechanisms to operate simultaneously. One of these mechanisms must be anisotropic, although the other may be isotropic. Another way is to cause comparable conduction to take place by electrons and holes simultaneously.

We have obtained anisotropy in the Seebeck effect from both of these causes in the same material, Bi_2Te_3, although over different temperature ranges and with different dopings.

HISTORY

Anisotropy in the Seebeck effect was first observed in 1927 by Boydston [1] in the semimetal bismuth. A preliminary search through the abstracts (in 1959) led us to believe that the theoretical calculation of the Seebeck coefficients of bismuth had not been carried out, so we proceeded with it ourselves. Later we discovered a paper published by B. S. Chandrasekhar [2] in October 1959, in which the calculation had been made. Our independent results for bismuth agree with his. We have also made a similar calculation for bismuth telluride.

H. J. Goldsmid [3] in 1957 observed the kind of anisotropy in the Seebeck effect in Bi_2Te_3 which we now believe is caused by mixed scattering. Goldsmid however showed, by a very approximate treatment, only that it could be caused by a relaxation time which was a different function of energy in different crystal directions. His approximations also predicted a relationship between the anisotropy of the Seebeck coefficients and the conductivity ratio of the form

$$S_1 - S_3 = \pm \left(\frac{k}{e}\right) \mathrm{d}\,(\sigma_1/\sigma_3)/\mathrm{d} \ln kT \qquad (1)$$

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where the subscript 1 refers to directions parallel to the cleavage plane, and 3 to directions perpendicular to it. The plus sign refers to p-type conduction.

We have shown that the necessary relaxation time tensor with anisotropic energy dependence can be obtained by the simultaneous action of two competing scattering mechanisms, and we have made a rather complete confirmatory analysis using the many-valleyed model of the band structure of Bi_2Te_3. This is the same model suggested and used successfully by Drabble [4, 5, 6] to interpret magnetoresistance data on this material.

THEORY OF THE SEEBECK COEFFICIENT FOR SINGLE-CARRIER CONDUCTION AND A MIXED SCATTERING MECHANISM

The perturbation of the equilibrium particle distribution function arising from electrical and thermal gradients is found by means of Boltzmann's equation. The flux of particles due to these gradients is then computed from the equation

$$\mathbf{J}^n = \frac{2}{h^3} \int f \nabla_p E \, \mathrm{d}\mathbf{p} \tag{2}$$

according to integration based on Drabble's many-valleyed model of the band structure of Bi_2Te_3, referred to before. The relation between the flux of particles and the gradients assumes the form

$$\mathbf{J}^n = \boldsymbol{\alpha} \cdot \nabla_r \bar{\mu} + \boldsymbol{\beta} \cdot \frac{\nabla_r T}{T} \tag{3}$$

when

$$\bar{\mu} = \epsilon - e\phi \tag{4}$$

$\bar{\mu}$ is electro-chemical potential
ϵ is the Fermi level
ϕ is the applied electrical potential

The Seebeck coefficient of a material such as Bi_2Te_3 is given by the limit of the Seebeck voltage measured across a thermocouple made of this material and another one (such as copper) whose Seebeck coefficient is much smaller, as the applied temperature difference of the two junctions approaches zero. Hence it is given by the gradient of potential per unit temperature gradient, with the current equal to zero, or

$$\mathbf{S} = \frac{\boldsymbol{\alpha}^{-1} \cdot \boldsymbol{\beta}}{eT} \tag{5}$$

The $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ tensors are anisotropic, but their ratio is not unless the relaxation-time tensor has a non-factorable energy dependence.

In an anisotropic crystal the lattice relaxation time will be of the form

$$\tau_{11} = aE^{-1/2} \qquad \tau_{33} = bE^{-1/2} \tag{6}$$

which has a factorable energy dependence. Hence lattice scattering alone, although anisotropic, will not give an anisotropic Seebeck effect. Suppose we postulate that another (possibly isotropic) form of scattering (by impurities, for example) with a relaxation time of the form

$$\tau = ce^q$$

operates simultaneously with lattice scattering and independently of it.

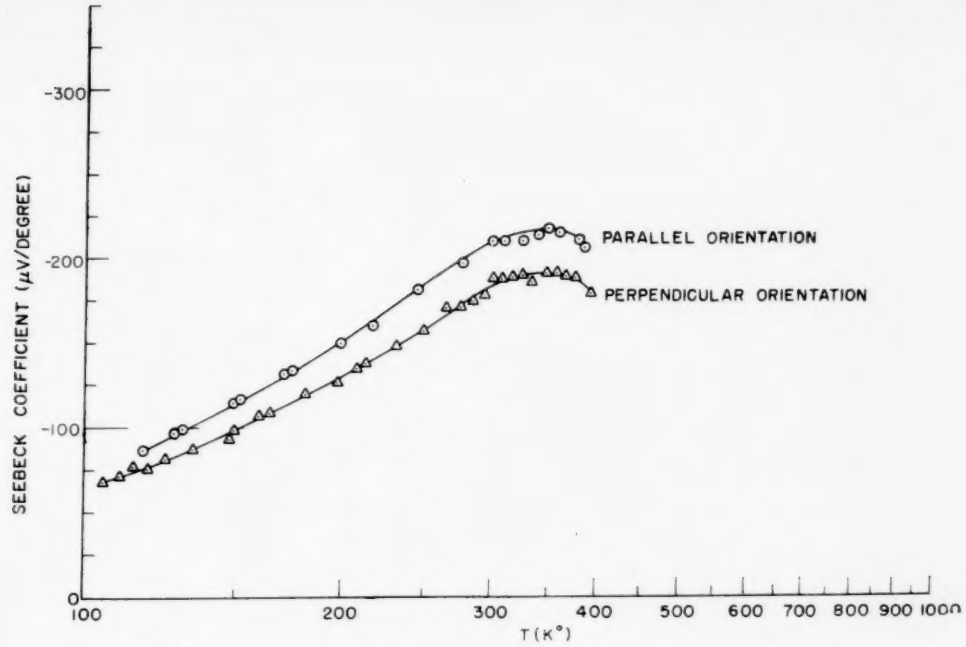

FIG. 1. Seebeck coefficients of iodine doped *n*-type Bi_2Te_3.

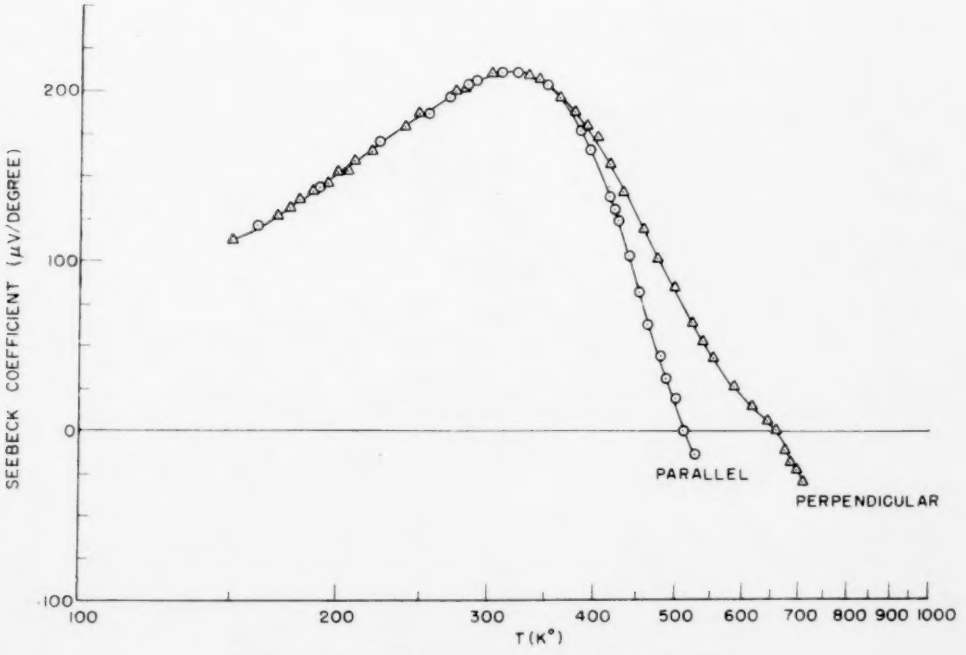

FIG. 2. Seebeck coefficients of undoped *p*-type Bi_2Te_3.

Then

$$\frac{1}{\tau} = \frac{1}{\tau_{\text{lattice}}} + \frac{1}{\tau_{\text{impurity}}} \tag{7}$$

so

$$\frac{1}{\tau_{11}} = \frac{1}{aE^{-1/2}} + \frac{1}{cE^{q}} \tag{8}$$

and

$$\frac{1}{\tau_{33}} = \frac{1}{bE^{-1/2}} + \frac{1}{cE^{q}}$$

Thus the relaxation time tensor will have a non-factorable energy dependence. Hence an anisotropic lattice scattering acting simultaneously with even an isotropic impurity scattering will give an anisotropic Seebeck effect.

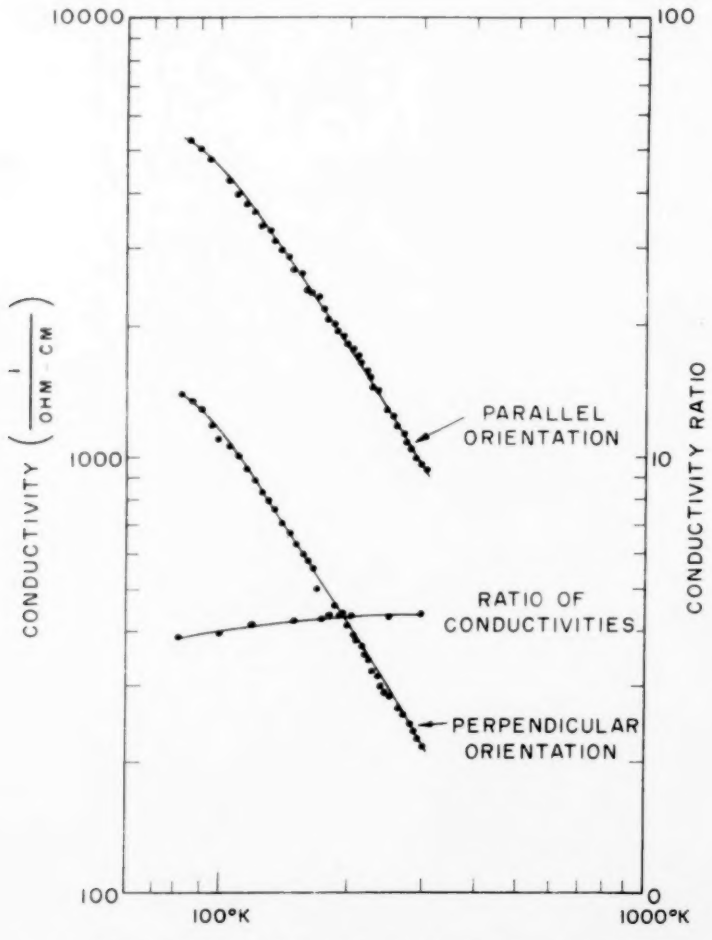

FIG. 3. Conductivity and conductivity ratio of iodine doped *n*-type Bi_2Te_3.

EXPERIMENTAL VERIFICATION

The Seebeck coefficient of iodine-doped (n-type) Bi_2Te_3 is shown in Fig. 1 and is seen to be anisotropic by 25 out of 200 μV/deg. This anisotropy is believed to be an indication that there is appreciable scattering by a mechanism other than lattice scattering in the iodine-doped material. This conclusion is consistent with the fact that the Seebeck coefficient of undoped p-type material, as shown in Fig. 2, is seen to be isotropic at temperatures below that at which mixed conduction begins.

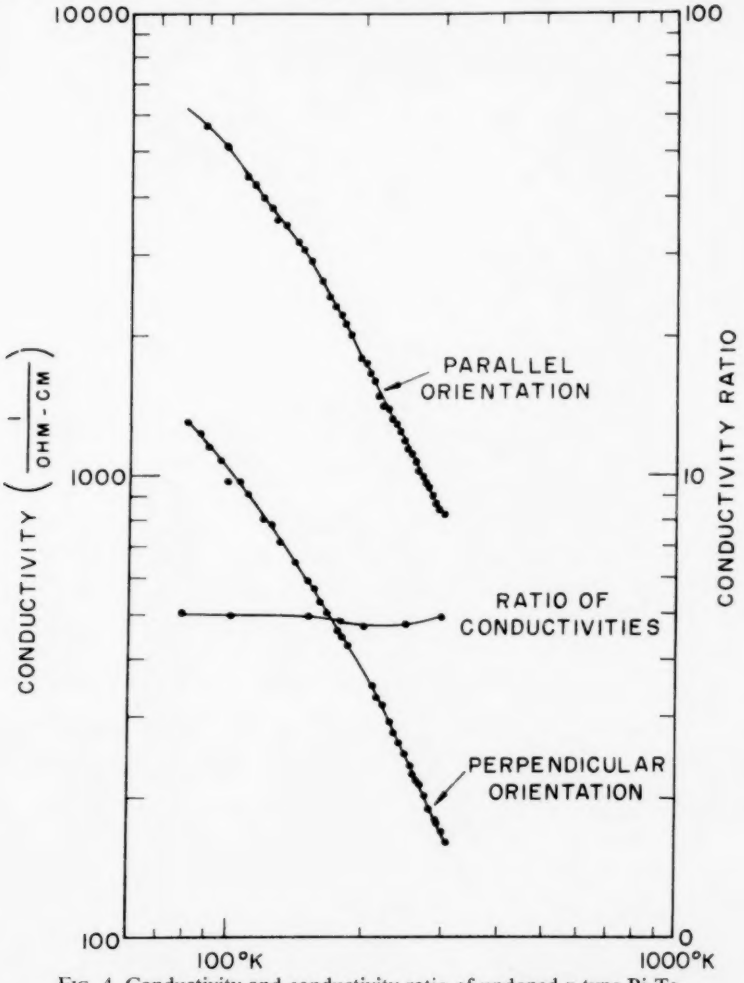

FIG. 4. Conductivity and conductivity ratio of undoped p-type Bi_2Te_3

The conductivity ratio of n-type iodine doped material plotted against log kT is shown in Fig. 3 and is seen to have a slope of 0·25. From equation (1) the difference between the Seebeck coefficients should be

$$S_1 - S_3 = -\left(\frac{k}{e}\right) \mathrm{d}(\sigma_1/\sigma_3)/\mathrm{d} \ln kT$$
$$= -(86{\cdot}2\mu\mathrm{V/deg}) \times 0{\cdot}25 \simeq -22\ \mu\mathrm{V/deg} \qquad (9)$$

which is very nearly that observed in Fig. 1. As mentioned previously, whereas this is the same calculation made earlier by H. J. Goldsmid, the present theory for the effect and the interpretation of the results is a good deal more complete than the earlier ones.

The slope of the conductivity ratio of undoped p-type material as shown in Fig. 4 is seen to be zero.

THEORY OF THE SEEBECK COEFFICIENT FOR TWO-CARRIER CONDUCTION AND A SINGLE SCATTERING MECHANISM

For the two-carrier case with a single scattering mechanism the current is given by

$$\mathbf{J} = (\boldsymbol{\alpha}_h + \boldsymbol{\alpha}_e)\,\nabla\overline{\mu} + (\boldsymbol{\beta}_h - \boldsymbol{\beta}_e)\,\frac{\nabla T}{T} \tag{10}$$

and

$$\mathbf{S} = \frac{(\boldsymbol{\alpha}_h + \boldsymbol{\alpha}_e)^{-1} \cdot (\boldsymbol{\beta}_h - \boldsymbol{\beta}_e)}{eT} \tag{11}$$

which assumes the form

$$S_{1,3} = -\frac{A + B\left(\dfrac{m_h^*}{m_e^*}\right)^{3/2}\left(\dfrac{\mu_h}{\mu_e}\right)_{1,3}}{C + D\left(\dfrac{m_h^*}{m_e^*}\right)^{3/2}\left(\dfrac{\mu_h}{\mu_e}\right)_{1,3}} \tag{12}$$

where A, B, C, and D are functions only of the Fermi levels. In fact B and D are either very large or very small for one-carrier systems, and of intermediate value for two-carrier systems.

It is seen from equation (12) that, if we assume only a single scattering process, the Seebeck coefficients will be anisotropic only if the ratio of the mobility of holes to the mobility of electrons is different in different directions, and if there is simultaneous comparable conduction by holes and electrons.

EXPERIMENTAL VERIFICATION

There is mixed conduction in Bi_2Te_3 beginning slightly above room temperature, and it is seen in Fig. 2 that the Seebeck effect does become anisotropic in this temperature range.

We have also made a theoretical calculation of Seebeck coefficients vs. temperature using the mobility ratios of Drabble, Groves and Wolfe [5] (which we assumed to be constant with temperature). We obtained the Fermi levels from the conductivity data of Shigitomi and Mori [7] and then compared the calculated Seebeck coefficient curve with Shigitomi and Mori's experimental Seebeck coefficient curve on the same sample from which the conductivity data was taken. The resulting plot is shown in Fig. 5 and is seen to follow their experimental points quite well.

CONCLUSION

It has been shown theoretically and verified experimentally, using as primary example the semiconductor Bi_2Te_3, that anisotropy of the Seebeck effect may be obtained basically in two ways. One way is to cause comparable conduction to take place simultaneously by holes and electrons, in the presence of a single scattering mechanism. Another way is to

cause two scattering mechanisms to operate simultaneously. One of these mechanisms must be anisotropic but the other may be isotropic. In general, a mixture of the above two conditions would also be expected to give an anisotropic Seebeck effect.

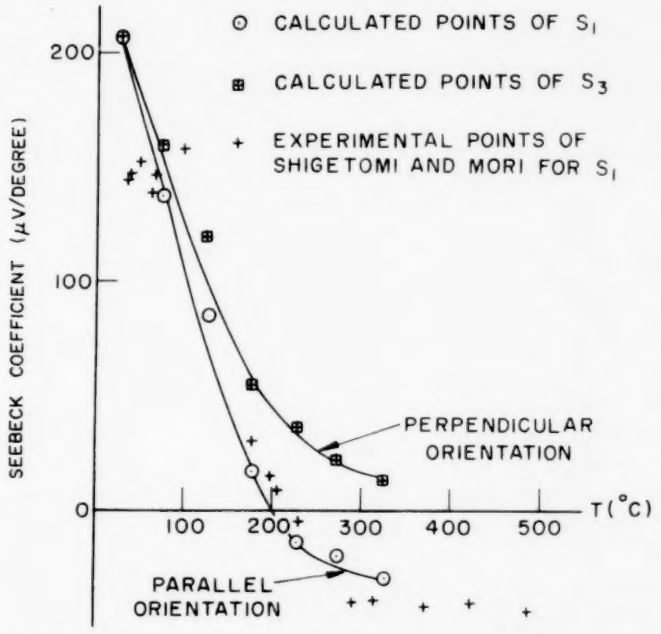

FIG. 5. Calculated curves of the Seebeck coefficients of *p*-type Bi_2Te_3 along with the experimental points of Shigitomi and Mori [7].

Acknowledgement—This work is based on a Ph.D. thesis completed in the Electrical Engineering Department of the Massachusetts Institute of Technology. The author wishes to express her gratitude to her thesis supervisor Prof. Richard B. Adler for his encouragement and many stimulating discussions.

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THERMAL CONDUCTIVITY IN SEMICONDUCTORS AT HIGH TEMPERATURE*

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ABSTRACT

THE THERMAL conductivity K of a semiconductor is composed of a lattice and an electronic contribution which are additive; $K = K_{ph} + K_{el}$. The lattice conductivity, K_{ph}, is determined by phonon–phonon scattering and/or scattering of phonons by static imperfections. The electronic contribution is given by $K_{el} = L\sigma T$ where L is the Lorenz number generalized to include the ambipolar effect [1], σ is the electrical conductivity and T the absolute temperature.

To study the above processes, the thermal diffusivity (thermal conductivity K divided by specific heat C) has been measured by a modification of Ångström's method [2], on Si, Ge, InSb, $AgSbTe_2$ and GeSi alloys. The temperature range of measurement was from 300°K to close to the melting points of the materials. In contrast to the standard ways of measuring K, the diffusivity method is accurate even at high temperatures.

The thermal conductivity K was derived from the measured values of the diffusivity K/C using published values of C. In cases where data for C were not available, its values were estimated from the Debye temperature and the Dulong–Petit law.

In the case of Si, Ge and InSb it was found that $K_{ph}/C = \alpha/[T - (\Theta/3)]$ where α is a constant of the material and Θ is the Debye temperature. Leibfried and Schlömann [3] derived, for the case of phonon–phonon scattering, the theoretical value $\alpha = 5{\cdot}7 \times 10^{-8} aM\Theta^3/(\gamma^2 C$ (cm^2 sec^{-1} deg), where a^3(Å^3) is the atomic volume, M is the mean atomic weight γ the Grüneisen constant, and C(Wdeg^{-1} cm^{-3}) the specific heat. Good agreement was obtained between the theoretical and measured values of α if one sets $\gamma = 2{\cdot}5$. However, this value of γ is much higher than the experimental values of 0·4, 0·7 and 0·5 reported [4] for Si, Ge and InSb respectively. The electronic contributions K_{el}, obtained from the measurements of K/C, were found to be in agreement with those computed from theory [1].

The results for the compound $AgSbTe_2$ and the alloys Ge–Si indicate that the dominant mechanism determining K_{ph} in this case, is scattering of phonons due to a disordered lattice. The relevance of some recent theoretical results for disorder scattering [5, 6] to the experimental results will be discussed.

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EFFECTS OF UNIDIRECTIONAL PRESSURE ON THE THERMAL E.M.F. OF Bi_2Te_3

W. TANTRAPORN*

Summary—The change of thermal e.m.f. in Bi_2Te_3 single crystals when unidirectional pressure is applied along the trigonal axis was measured at room temperature. The fractional change of the thermal e.m.f. along the trigonal axis under such pressure appears to approach a saturation value of a few per cent, and is positive for the *p*-type, negative for the *n*-type. The magnitude of the change varies with the carrier density, and may be explained qualitatively in terms of the change of the carrier density by the pressure.

INTRODUCTION

THE EFFECT of pressure on the performance of a thermoelectric material has not been very extensively investigated. Yet, the presence of internal stress is to be expected when the material is under a thermal gradient, whether it is exposed or encapsulated. It is interesting

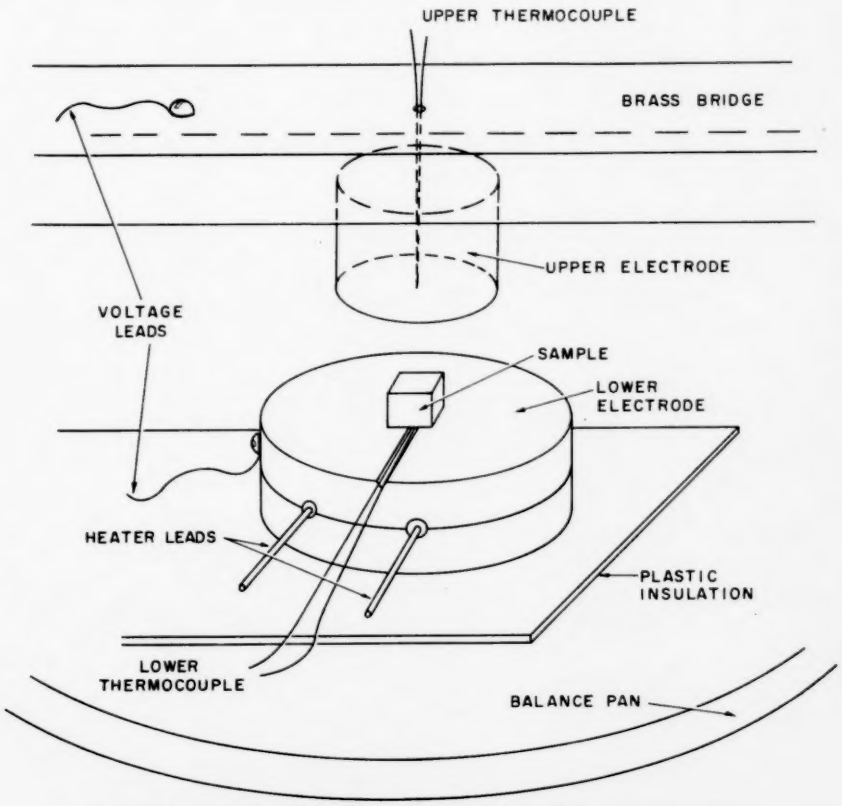

FIG. 1. Schematic drawing of the sample and electrode-press arrangement.

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to see to what extent a thermoelectric material may be affected by stress. To this end, single crystal of Bi_2Te_3 was chosen. Firstly, because the crystal is mechanically soft, and therefore large strain could be expected from simple, small stress apparatus. (Note that theoretically one expects the strain to be the independent variable in calculating the effects on the material properties). Secondly, Bi_2Te_3 is already a good representative of thermoelectric-materials. Lastly, piezogalvanomagnetic [1] and piezoresistive [2] measurements on Bi, which has similar structure as Bi_2Te_3, showed anomalously large effects due to anisotropic deformations. By investigating the effect of the unidirectional pressure along the mechanically weak trigonal axis of Bi_2Te_3, the results would likely be applicable to the polycrystalline case, for it may be expected that microscopic crystals in the polycrystalline aggregate would be deformed practically only along that axis.

EXPERIMENTAL

A schematic diagram of the experimental arrangement is given in Fig. 1. The electrodes were of nickel plated copper. The temperature difference of about 10–20 °C was maintained across the sample by means of Kanthal wire heater. The thermocouples used were 5 mil chromel–alumel. The samples were in right parallelopiped form, approximately 5 mm on each side. The pressure along the trigonal direction was applied by the balance pan pushing against the rigid upper bridge. (Not shown is a lucite guide to prevent the relative transverse motion of the two electrodes.) Due to the large thermal capacity of the electrodes and the shield afforded by the lucite guide, the sample was maintained at equilibrium such that the voltage measured through the electrodes is stable to within $\pm 0{\cdot}1$ per cent. The range of pressure applied was up to 2×10^8 dyn/cm^2.

The measurement of the Seebeck voltage as a function of pressure, however, contains relatively large nonreproducibility, speculated to be due to the imperfect elasticity of the samples. Such measurements of the changes in the Seebeck voltage in various samples are shown in Fig. 2. The vertical line at each point indicates the spread of two successive measurements. Defining, for convenience,

S_{33} = the ratio of the voltage developed along the trigonal direction to the temperature difference along the same direction,

P_{33} = the pressure due to the force along the trigonal direction on the surface normal to that direction,

then the piezothermoelectric coefficient is defined by

$$\Gamma_{33} \equiv \lim_{P_{33} \to 0} \frac{S_{33}(P_{33}) - S_{33}(0)}{P_{33} \cdot S_{33}(0)}.$$

Also let

$$\Delta_{33} \equiv \frac{\text{maximum value, if exists, of } S_{33}(P_{33}) - S_{33}(0)}{S_{33}(0)}.$$

The results are then conveniently summarized in Table 1.

The reader is reminded of the fact that the absolute values of S_{33} given are not very accurate due to the relatively large errors in the two thermocouples' readings. The relative values, and hence Γ_{33} and Δ_{33} are, however, accurate to within the error spread given in Fig. 2.

TABLE I. SUMMARY OF RESULTS ON INDIVIDUAL SAMPLES

Sample type and No.	Seebeck coefficient at zero pressure, $S_{33}(0)$ (μV/deg)	Piezo-thermoelectric coefficient at low pressure, Γ_{33} (cm²/dyn)	Maximum change in Seebeck coefficient, Δ_{33} (%)
$p1$	+207	$+5{\cdot}5\times10^{-10}$	4·1
$p2$	+221	$+1{\cdot}7\times10^{-10}$	1·4
$n1$	−155	$-1{\cdot}7\times10^{-10}$	−1·2
$n2$	−316	0	0

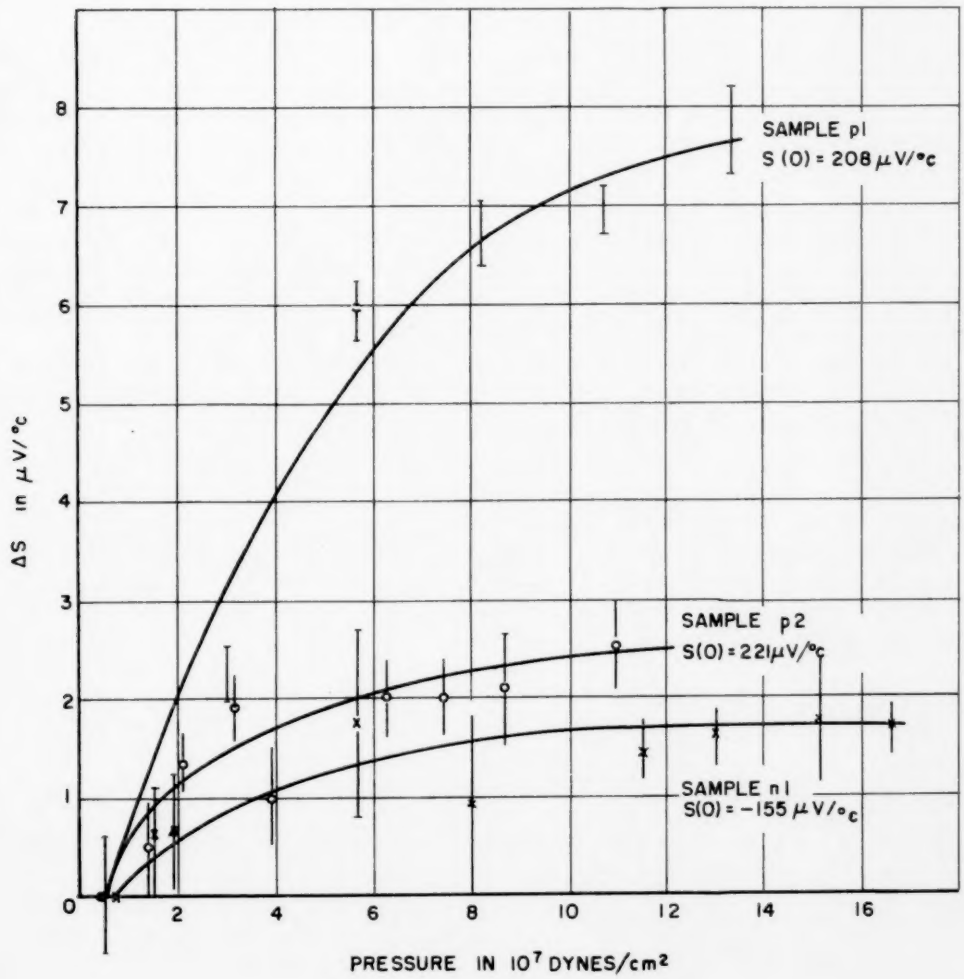

FIG. 2. Changes in the Seebeck coefficient as a function of pressure.

DISCUSSION

If one writes n, μ_n, and p, μ_p as the density, mobility of electrons and holes respectively, then qualitatively:

the Seebeck coefficient $S \sim (p\mu_p - n\mu_n)/(p\mu_p + n\mu_n)$;

the electrical conductivity $\sigma \sim (p\mu_p + n\mu_n)$.

The effect of pressure is generally thought of as to change the mobility of the charge carrier. If one disregards the minority carriers in the samples used, then the Seebeck coefficient depends, if any, only weakly on the mobility compared to the dependence of σ on μ. Thus, the effect of pressure can be expected to be larger for the piezoresistive effect than for the piezothermoelectric one. An experiment was performed on the sample $p1$, whose piezothermoelectric effect is as large as 4 per cent. There was no piezoresistive effect observed to within 1 per cent.

If one invokes the possibility of the change in the carrier density, then the results in Table 1 can be qualitatively understood in terms of the hypothesis that the effect of pressure is to cause an increase in p. For then the absolute magnitude of the Seebeck coefficient in the p-type would increase and that in the n-type would decrease. The amount of change would be relatively larger for the relatively smaller unstressed value. This hypothesis was used by Kuczynski [2] in explaining the piezoresistive effect in antimony. Due to the anisotropic compliance, the compression along the trigonal axis is accompanied by only a small lateral dilatation. The specific volume decreases, and therefore the size of the Brillouin zone in the reciprocal space increases. The valence zone thus can accommodate more electrons. In other words, such pressure would create new holes, or decrease the number of the electrons in the conduction band, explaining the observed results.

It should perhaps be remarked that the geometry of the experiment also precludes the possibility of the anisotropic population transfer among the multiple valleys of the band structure.

CONCLUSION

With pressure up to the yield point of the crystal ($\approx 2 \times 10^8$ dyn/cm^2), the change of the Seebeck coefficient in heavily doped Bi_2Te_3 amounts to only a few per cent. With the known data available [3], the best piezoresistive coefficient is approximately 3×10^{-10} cm^2/dyn in other semiconductors. It appears that in general the effects of pressure on the Seebeck coefficient and electrical conductivity will be of minor interest and little worries to the thermoelectricians.

Acknowledgement—The author wishes to thank Dr. J. R. Drabble for the single crystals of Bi_2Te_3 used in this investigation.

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EFFECT OF HYDROSTATIC PRESSURE ON THE RESISTANCE AND THE SEEBECK COEFFICIENT OF *n*-TYPE GaSb*

A. Sagar and R. C. Miller†

ABSTRACT

The Seebeck coefficient and resistance of *n*-type GaSb under hydrostatic pressure (up to 18,000 atm) was measured between 200°K and 400°K for samples with different carrier concentrations. Both these properties increased continuously with pressure up to 10,000 atm after which they seemed to approach a constant value. For example the Seebeck coefficient for a sample with $R_H \sim 10\ \text{coul}^{-1}\ \text{cm}^3$ at normal pressure was found to be 180 μV/°C at 200°K; 290 μV/°C at 300°K and 345 μV/°C at 400°K. These values increased to 480 μV/°C at 200°K; 500 μV/°C at 300°K and 490 μV/°C at 400°K respectively at 10,000 atm. The resistance of the same sample increased by a factor of 4·4 at 200°K; 2·8 at 300°K and 2·2 at 400°K within a pressure range of 9000 atm. Similar effects were found for samples with different values of Hall coefficient.

These effects can be explained on the basis of our knowledge of the conduction bands for this material, with the lowest band-minimum in the center of the Brillouin Zone and the next minimum along (111) directions in *K*-space. The energy separation between the two bands under normal condition is about 0·08 eV; and the density of states in the upper bands is about 40 times that in the lower band. So that under normal conditions the carriers are distributed in the two bands according to the Fermi Dirac or Boltzmann statistics, as the case may be. Under hydrostatic pressure, the two bands approach each other and at about 10,000 atm, the energy separation between the two is about zero. Thus at about this pressure practically all the carriers are in the (111) band and the transport properties exhibited by this material at such pressures will be characteristic of this band.

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OPTICAL AND THERMAL ENERGY GAPS IN POLAR SEMICONDUCTORS

EDWARD MILLER, KURT KOMAREK and IRVING CADOFF*

ABSTRACT

THE MINIMUM energy gap of a semiconductor is usually obtained from either the infrared absorption edge, or from measurement of the resistivity or Hall coefficient as a function of temperature. While in elemental semiconductors the values for the energy gap obtained by these two techniques agree fairly well, in compounds marked discrepancies may be observed, in that the optical gap is less than the thermal gap.

The optically observed energy gaps of PbTe and PbSe extrapolated to 0°K are approximately 0·2 eV less than those obtained from thermal measurements. The samples were sealed in evacuated Pyrex capsules during elevated temperature measurements to prevent any composition change due to the unequal vapor pressure of the two constituents. Room temperature resistivity values obtained before and after the thermal measurements were in agreement. Our experiments indicate that the difference cannot be explained by excess carrier formation at elevated temperatures due to retrograde solubility in the systems studied. Formation of defect is a more likely mechanism.

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SESSION III

SYNTHESIS AND EVALUATION OF MATERIALS (A)

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COMPLEX THERMOELECTRIC ALLOYS EXHIBITING POISING BEHAVIOR*

JOHN B. CONN, EDWARD J. SHEEHAN and ROBERT C. TAYLOR †

INTRODUCTION

THE ALLOY system $Bi_xSb_{(2-x)}Te_3$ has been studied at length by various investigators interested in the development of improved thermoelectric materials. Wright [1] reported a minimum in the phonon component of thermal conductivity at the composition $BiSbTe_3$ without reduction in electron mobility. Smirous and Stourač [2] described an alloy based on Bi_2Te_3 . $3Sb_2Te_3$ and containing about 4 per cent excess tellurium together with 0·05 per cent germanium doping agent; a figure of merit in excess of $3{\cdot}5 \times 10^{-3}/°K$ was claimed for it. In these laboratories, P. I. Pollak and H. Flynn encountered an anomaly in the system $Bi_xSb_{(2-x)}Te_3$ at the composition $BiSbTe_3$, characterized by irreproducibility in Seebeck coefficient with tendency to become *n*-type. Addition of excess tellurium does not render the composition stably *n*-type; on the contrary, it becomes reliably *p*-type.

Stoichiometric antimony telluride is in itself rather peculiar by comparison with bismuth telluride since it exhibits degenerate behavior. While the metals are nominally trivalent in both compounds, they contain *s* electrons which, in the case of bismuth, hardly ever are involved in bonding, whereas in antimony, involvement is common; moreover, the existence of mixed-valence compounds of antimony is well documented. (One can cite, for example, the stable oxide Sb_2O_4 and the complex salt Cs_2SbSl_6.) The question is therefore raised as to whether one can account for the behavior of an alloy such as that described by Smirous and Stourač in terms of a classical poised system, at least to a first approximation. If this be the case, one should be able to arrive at a system formulated as $(Bi_xSb_{(2-x\pm y)})^{+}(Te_{(3\mp y)})^{-}$ which would react very sluggishly to changes in composition.

This hypothesis has been tested on the alloy Bi_2Te_3 . $3Sb_2Te_3$ to which a small amount of selenium has been added, as suggested by Wright. Specifically, the central composition chosen was $Bi_4Sb_{10}SeTe_{25}$, which can be written as:

$$Bi_4^{3+}\ Sb_5^{3+}\ Sb_5^{5+}\ Se^{=}\ Te_{25}^{=}$$

i.e., electrically neutral. Despite the considerable excess of tellurium which it contains, the alloy is *p*-type and exhibits average parameters $S = +195\ \mu V/°K$, $\rho = 13{\cdot}0 \times 10^{-4}$ ohm cm, and $\kappa = 0{\cdot}0155\ W\ cm^{-1}\ deg^{-1}$. Using a Bridgman furnace with bilateral heat shields so placed as to expose less than half of the ingot to direct radiant heat, ingots can be obtained which consist of parallel-oriented crystals. These show perfect vertical cleavage and good resistivity profiles.

The X-ray diffraction pattern suggests a solid solution of bismuth and antimony tellurides, but extra lines are present which could be ascribed to tellurium or a phase rich in bismuth telluride. However, the cleavage properties and flat resistivity profile were hard to reconcile with an inhomogeneous system; the alternative was to assume that the alloy

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is homogeneous but possesses a lattice of symmetry lower than the $R\bar{3}m$ characteristic of Bi_2Te_3 and Sb_2Te_3. It was found that the extra reflections could be incorporated if the a axis of the triply primitive unit cell were multiplied by 4, giving for the alloy $a = 17{\cdot}14$ Å, $c = 30{\cdot}44$ Å. The measured density is $6{\cdot}85$ g/cm^3, which requires 6 ($Bi_4Sb_{10}SeTe_{25}$) per unit cell, for a total of 240 atoms, i.e., a superstructure.

Whether or not a superstructure does exist, one can define a unit:

$$Bi_{24}Sb_{(60+x)}Se_6Te_{(150-x)}; \qquad -8 \leq X \leq +12$$

which can be manipulated integrally so as to yield twenty alloys, with varying ratios of Sb^{3+} and Sb^{5+} populations. This procedure was adopted as a means for locating the composition having optimum combination of parameters.

EXPERIMENTAL

Materials

Bismuth, selenium, and tellurium were American Smelting & Refining Co. 99·999 per cent quality. Antimony of listed purity 99·999 per cent was obtained from United Mineral and Chemical Corp.

Equipment

The Bridgman unit was made from a split-coil combustion furnace with transite inserts

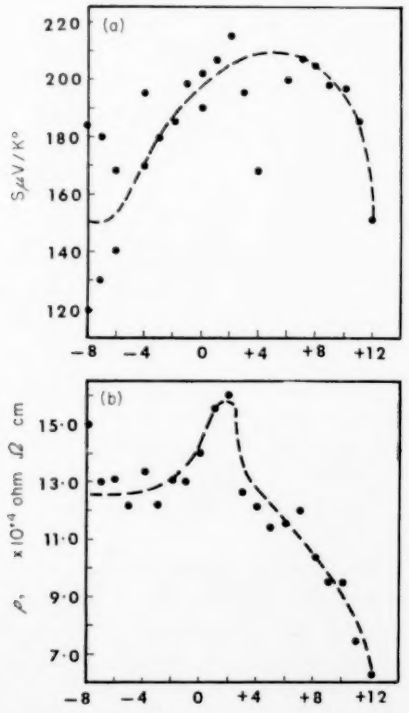

FIG. 1(a) and (b). Seebeck coefficient and electrical resistivity of alloys in the system $Bi_xSb_{(2-x)}Te_3$ as a function of x.

clamped between the halves in such a position as to shield more than 50 per cent of the ingot from direct radiation. Interesting alloys were also prepared by zone-levelling.

Procedure

Component elements were crushed as required in mullite mortars and weighed out on an analytical balance. Master mixes totalling either 25 or 100 g were charged into quartz tubes which had previously been coated with carbon by cracking at 900–950° acetone vapor carried in a nitrogen stream. The tubes were evacuated to 1 μ, sealed, and heated horizontally in a hinged, split-coil combustion furnace. When fusion was complete, the furnace was rocked to ensure mixing, after which the melt was quenched. The billets were crushed sufficiently to charge into 8 mm quartz crystallization tubes, which were likewise evacuated, sealed, and then passed through the Bridgman equipment at 6·75 in/hr. Maximum furnace temperature was 685°C.

Measurements

Seebeck coefficients were measured against aluminium, with the cold end at room temperature, and a 10-degree differential. Resistivities were determined by use of two-point probe equipment. Thermal conductivities were obtained by measuring heat input necessary to maintain one end of the piece at room temperature, while the other was cooled in an ice-sink.

RESULTS AND DISCUSSION

Graphs of Seebeck coefficient, resistivity, thermal conductivity, and figure of merit versus the compositional factor X are given in Figs. 1(a) and (b); 2(a) and (b). Data below $X = 4$ are of poor reliability because of tellurium vapor pressure difficulties. The Seebeck coefficient shows a broad maximum centering at about $X = +6$. Resistivity passes through a sharp peak at $X = +2$ and diminishes thereafter, while thermal conductivity likewise is at a maximum for $X = +2$, but at a minimum for $X = +8$. The combination of these variables leads to a steep maximum in figure of merit at $X = +8$, where it attains $2{\cdot}8 \times 10^{-3}$ °K^{-1} and has perhaps reached as high as $3{\cdot}2 \times 10^{-3}$ °K^{-1}. This composition, ($Bi_{24}Sb_{68}Se_6Te_{142}$), has been subjected to considerable preparative study. Most consistent parameters are observed on zone-levelled ingots, where $S = +205 - 215$ μV/°K, and $\rho = 9{\cdot}5 - 10{\cdot}5 \times 10^{-4}$ ohm cm. These are independent of source material origin, provided that the elements are of comparable purity. On the other hand, the thermal conductivity has shown considerable variation with antimony sample; the lowest figures (0·0115–0·0127) were obtained with one lot which had a surface so drossy as to require cleaning with concentrated hydrochloric acid before use. Other lots have led to ingots with thermal conductivity as high as 0·0143 W cm^{-1} deg^{-1}; the variation appears connected with the gross structure of the ingot, but attempts to pin it down have thus far not been very successful. There is indication that oxygen may play a role; however, experiments involving addition of small amounts of antimony oxide have been inconclusive, since in its presence, quartz tubes break unless they have been carbon-coated prior to fusion. The reducing action of the carbon obscures the oxygen effect.

Hall-effect measurements on Alloy 68 show hole concentration to be $2{\cdot}2 \times 10^{19}$ cm^{-3} and mobility 320 cm^2 V^{-1} sec^{-1}. Alteration in the number of selenium atoms per unit of 240 from 0–12 disclosed that the optimum number is 6; for $N < 6$, thermal conductivity in-

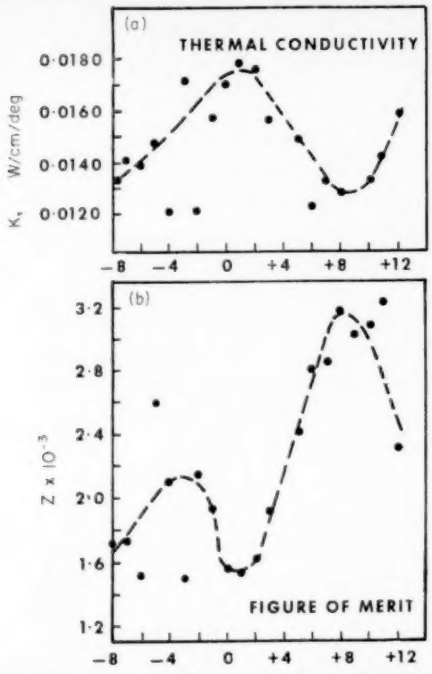

FIG. 2(a) and (b). Thermal conductivity and figure of merit of alloys in the system $Bi_xSb_{(2-x)}Te_3$ as a function of x.

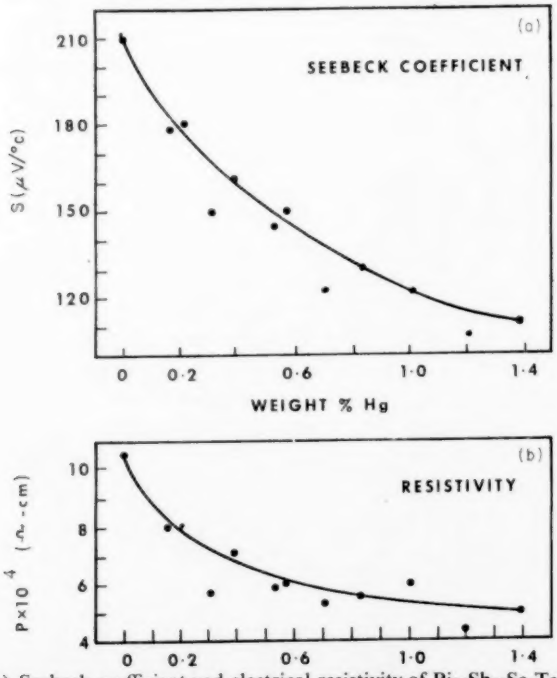

FIG. 3(a) and (b). Seebeck coefficient and electrical resistivity of $Bi_{24}Sb_{68}Se_6Te_{142}$ (Alloy 68) with various additions of mercury. In both cases, the abscissa is weight per cent mercury.

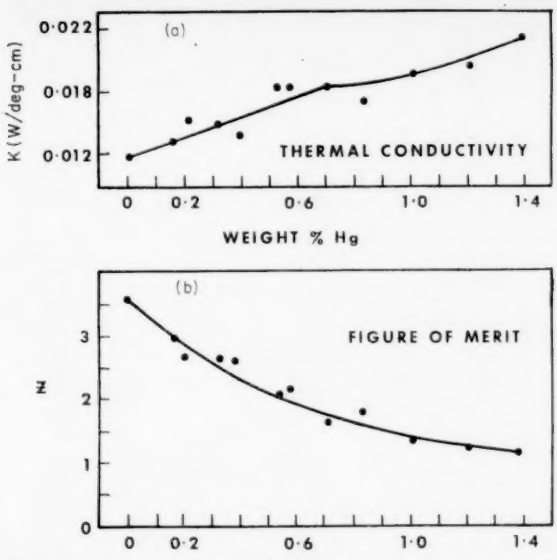

FIG. 4(a) and (b). Thermal conductivity and figure of merit of mercury-doped specimens of Alloy 68 as a function of the concentration of mercury.

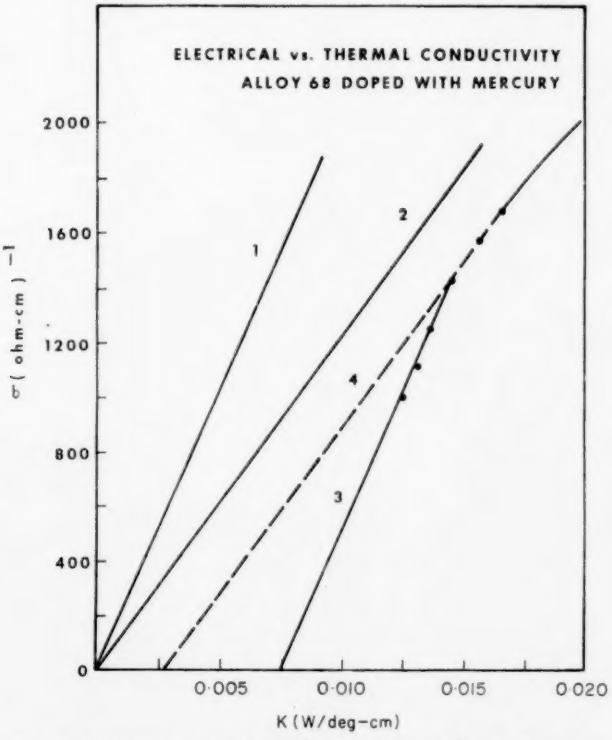

FIG. 5. Electrical conductivity of mercury-doped Alloy 68 as a function of its thermal conductivity.

creases and for $N > 6$ resistivity increases, both in a non-compensatory way, so that the figure of merit is less on either side.

None of the alloys thus far discussed contain any extraneous doping elements. The effect of copper and mercury on the alloy $X = 8$ has been investigated; both are acceptors, but the behavior of mercury was uniform, while that of copper was erratic. Graphs of Seebeck coefficient, resistivity, thermal conductivity, and figure of merit as functions of mercury concentration are given in Figs. 3 and 4. In Fig. 5, electrical conductivity is plotted against thermal conductivity for the purpose of determining the phonon component. Line 1 represents the Wiedemann–Franz law for non-degenerate semiconductors, and line 2 for the degenerate case. The points on line 3 are taken from the data of Figs. 3(b) and 4(a). The lower four, representing the doping range 0·0–0·4 per cent mercury, fall on a branch paralleling the non-degenerate line; from 0·4–0·75 per cent mercury, a second branch parallels the degenerate line. Extrapolation of line 3 to zero conductivity gives $K_{ph} = 0{\cdot}007_7$ W cm^{-1} deg^{-1} for the alloy $X = 8$.

CONCLUSIONS

The existence of a resistivity peak in the vicinity of the composition where the statistical valence of antimony is calculated to be 4+, together with the sluggish change in Seebeck coefficient over the range $X = -2$ to $+10$ lends support to the use of the poising concept as a methodology in exploring complex non-stoichiometric thermoelectric materials systems involving elements capable of more than one valence state. The anomalous relationship between resistivity and thermal conductivity which occurs over much of the compositional range for the alloys above described, gives rise to hope that similar but even more efficient combinations can be found.

Acknowledgement—Measurements of thermoelectric parameters were carried out by G. V. Downing and C. J. Barclay.

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NOTE ADDED IN PROOF

Since the preparation of the manuscript for this paper in October 1960, it has been shown by metallographic examination that the bismuth—antimony selenide—telluride system in the region of excess tellurium is not homogeneous, but contains a tellurium-rich phase which is distributed uniformly between parallel crystals of the telluride solid solution. The poising concept which was advanced must therefore be discarded. The fact remains, however, that optimum thermoelectric performance is achieved only in the presence of the tellurium phase and at the composition found. The reason for this behavior is obscure, but may reside in the gross structure of the ingot.

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GROWTH OF SINGLE CRYSTAL BISMUTH TELLURIDE

FREDERICK J. STRIETER*

Summary—Single crystals of bismuth telluride have been grown by the Teal–Little method to prepare material suitable for the evaluation of the physical properties. The non-cubic symmetry of the crystals is evident from the lamellar shape in which they grow. Crystals were pulled perpendicular to the *c*-axis. Crystals grown from an initially stoichiometric melt were all *p*-type. Crystals of *n*-type material were successfully grown using iodine doping.

Some of the problems encountered in growing the crystals are discussed. They included various types of polycrystalline growth, scum formation on melt surfaces, and difficulty in pulling more than 4 or 5 single crystals from one charge.

INTRODUCTION

IN STUDYING the physical, electrical, and thermoelectric properties of bismuth telluride, one must make the studies under known, reproducible conditions. In a non-cubic crystalline material like bismuth telluride, the properties are dependent on the orientation of the specimen. With the random crystallite orientation in polycrystalline material, there is no way of knowing the exact crystallite orientation in various samples. For this reason it is desirable to have single crystal material available when making physical, electrical and thermoelectric measurements.

This work is by no means the first report on single crystal bismuth telluride. Large single crystal regions have been reported in material obtained by the Stockbarger method [1, 2]. Values of the thermoelectric properties of single crystal material have also been reported [2, 3]. This paper emphasizes some of the problems encountered in growing single crystal Bi_2Te_3.

EXPERIMENTAL PROCEDURES

Single crystals of bismuth telluride were grown by the Teal–Little method. The crystal puller consists of a heat source, material container, and seed-crystal holder. Electrical resistance heating is used to melt the sample.

The heater is enclosed in a quartz jacket to prevent contamination of the material. The 110 V a.c. power is regulated by a constant voltage transformer. Current is adjusted with two Variacs in series; these provide a stable, easily-regulated power source.

A quartz crucible, supported by the heater liner, holds the melt, and the seed crystal is held in a steel chuck. This chuck is attached to a shaft, rotated and pulled up by two separate motors, each independently variable. The entire assembly is enclosed in an open-end Pyrex tube, with one end seated on a baseplate. The other end is fitted with a plate through which the shaft passes.

A charge of ingot bismuth telluride (100 g) was cleaned and etched in dilute aqua regia solution, rinsed with distilled water, and allowed to dry. The ingot then was placed in the crystal puller and the assembly closed. Air was flushed from the puller with helium gas at a flow rate of 8–10 ft^3/hr. The bismuth telluride was melted with the pressure in the container at 2–3 mm of Hg above atmosphere. Because of the large thermal capacity of the puller, equilibrium temperature was reached slowly. Therefore the melt was allowed to stand at

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pulling temperature 10–15 min after the last of the Bi_2Te_3 melted. When a small portion of the melt froze out along the surface of one side of the crucible and remained constant in size, the seed crystal was lowered into the melt. The seed crystal was rotated at 8–10 rev/min and was pulled at a rate of 2–3 in per hr.

In all of these experiments crystals grown from an initially stoichiometric melt were *p*-type. Even when a slight excess (2–3 per cent) of tellurium was added, the crystals remained *p*-type. This agrees with results reported in other experiments [4]. Crystals of *n*-type material were grown using iodine doping.

Because of impurities present on the ingot, a clean melt is often difficult to obtain. However, results are satisfactory if the ingot is etched with a 50% aqua regia solution until the black tarnish often formed initially is removed. Precipitation of water-insoluble bismuth salts on the ingot can be prevented if the first few washings with distilled water are made acidic by adding a few drops of aqua regia. Often the ingot will have "blow holes" which should be carefully rinsed with distilled water. With these precautions, scum formation is minimized and should not interfere with crystal growth.

From two to three grams of tellurium is lost by evaporation in each run. This tellurium vapor condenses on the Pyrex jar, but visibility is not seriously affected.

Because the crystals grown were small (about 10 g), more than one crystal was pulled from each charge. After the fifth or sixth was pulled from the melt, crystal growing became exceedingly difficult, if not impossible. Undoubtedly the deviation from stoichiometry plays a part in the difficulty. Several experiments were performed in which two grams of tellurium were added to the melt in order to replace that lost by evaporation in the previous run, but there was no improvement in results.

Obtaining a single crystal seed presented one of the more difficult problems. The most successful method of obtaining a seed was to "neck down" to a very small point by allowing the melt to reach a temperature that melted the seed at the tip. The melt temperature was then lowered and the small point dipped in and allowed to grow. Several large crystals were obtained in this way.

NATURE OF THE CRYSTALS

Crystals vary in size. Length is limited to 3 in by the construction of the puller. The other dimensions are controlled by the size of the seed crystal and, more important, the temperature at which the crystal is pulled. A cross-section is almost rectangular, with typical dimensions of about 2 mm and 9 mm. The crystals have a characteristic shape with two large parallel triangular sides (Fig. 1).

Bismuth telluride has a rhombehedral crystal structure (space group $R\bar{3}m$). This space group can be described by reference to hexagonal axes, and a hexagonal unit cell. The cell dimensions are $a = 4{\cdot}384$ Å, $c = 30{\cdot}45$ Å [5]. The bismuth and tellurium atoms are arranged in layers perpendicular to the c axis; each layer contains only one kind of atom. The layers are arranged Te–Bi–Te–Bi–Te–Te–Bi–Te–Bi–Te. This atomic layer arrangement accounts for the shape of the crystals and for their cleavage planes. The chemical bonding between the two Te layers is weaker than between Bi–Te layers [6]. Consequently it is easy to cleave the crystal between the two Te layers. All crystals were pulled in a direction parallel to the cleavage planes (perpendicular to the (0001) direction). Attempts to pull crystals perpendicular to the cleavage planes were unsuccessful.

Crystals grow in step formation often initiated by some small impurity (Fig. 2). The steps

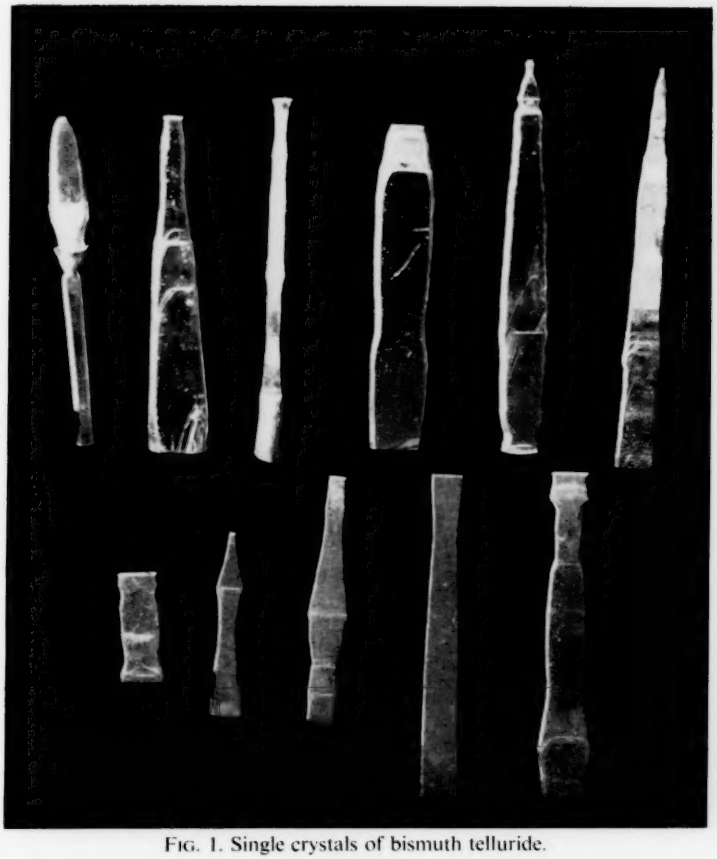

FIG. 1. Single crystals of bismuth telluride.

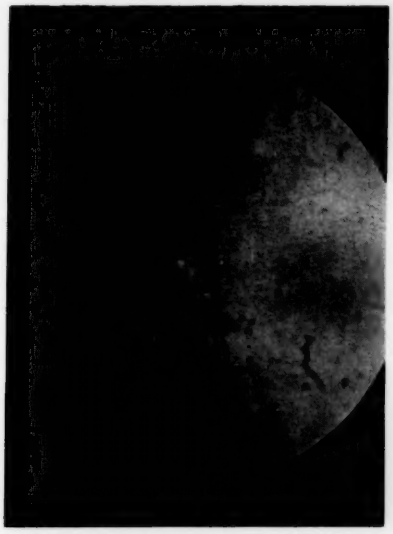

FIG. 2. Impurity-initiated step formation in bismuth telluride.

[facing p. 126]

range from 300–3000 Å. The size of the steps is governed by temperature, with lower temperatures producing larger and more numerous steps.

Many crystals start growing singly from the seed, but then become twinned or have satellite crystal formations. Twinning is difficult to detect in the course of growth, but satellite formations are easily seen because of their effect on the two large flat surfaces. The two main types of satellite formations are tetrahedral and pyramidal. Tetrahedral growth probably arises when an impurity nucleates additional crystallites, and is most common when the melt is not clean. Pyramidal growth is very rapid and takes place along the whole side of the crystal at once. Sometimes it occurs simultaneously on both sides, but more often on one side first, and then on the other. Pyramidal growth can be curbed by controlling the melt temperature so that there is little step formation. Definite correlation exists between pyramidal growth and step growth.

THERMOELECTRIC MEASUREMENTS

Only preliminary measurements of the various thermoelectric properties have been made. Because of experimental difficulties the thermal conductivity perpendicular to the cleavage planes has not been measured. Typical values of the room-temperature thermoelectric properties of these crystals are given in Table 1. In order to assess the performance under operating conditions a small couple was constructed with no attempt to optimize the parameters. This couple produced a temperature difference of 49°C between the hot and cold ends.

TABLE 1. ROOM-TEMPERATURE THERMOELECTRIC PARAMETERS OF SINGLE-CRYSTAL BISMUTH TELLURIDE

	Seebeck coefficient (μV/°C)	Electrical resistivity (Ω-cm)	Thermal conductivity (W/cm°C)
p-type—parallel to cleavage planes	+197	0·0077	0·0189
p-type—perpendicular to cleavage planes	+190	0·0194	—
n-type—parallel to cleavage planes	−283	0·0033	0·023
n-type—perpendicular to cleavage planes	−240	0·0148	—

Acknowledgements—I should like to thank Paul Goundry for providing the Bi_2Te_3 ingots and A. M. Bryant, John Stamper and Don Watson for measuring the thermoelectric properties.

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THE EFFECT OF FREEZING CONDITIONS ON THE THERMOELECTRIC PROPERTIES OF $BiSbTe_3$ CRYSTALS*

J. P. McHugh, G. J. Cosgrove and W. A. Tiller†

ABSTRACT

The effects of growth rate and interface temperature gradient on the thermoelectric parameters, α, $1/\rho$, and $1/(K-K_e)$ were studied using Bridgman-grown, oriented polycrystals. All three parameters were found to increase as the freezing rate decreases and the temperature gradient in the liquid at the interface increases. The effects are primarily attributed to the variation in the degree of micro-segregation produced in the crystals by the freezing conditions.

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THE EFFICIENCY OF LEAD AS AN ACCEPTOR IN BISMUTH TELLURIDE*

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ABSTRACT

PREVIOUS reports have shown that lead preferentially occupies an interstitial site in bismuth telluride, rather than a substitutional site. As a result, the lead does not contribute one hole for each lead atom added to the bismuth telluride. It is our contention that this occupancy of an interstitial site is actually a function of the high concentration (approximately 10^{19} atom/cm^3) of lead in the bismuth telluride and of the rather poor crystal structure usually obtained in bismuth telluride.

Our work has shown that, for proper crystal-growth conditions, the acceptor efficiency of lead approaches unity as a limit, i.e. all of the lead occupies substitutional sites in the bismuth telluride lattice, and consequently donates a hole to the lattice.

* A complete discussion of this work will be published in an early issue of this journal.

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THERMOELECTRIC PROPERTIES OF THE Bi_2Te_3–Bi_3Se_3 ISOMORPHIC COMPOUND SYSTEM

M. H. LaChance and E. E. Gardner*

Summary—Properties of undoped $Bi_2Te_{(3-x)}Se_x$ compounds were measured at 300°K over the composition range $x = 0$–3. Mode of conduction was observed to change from *p* to *n* at the composition $x = 1$. The compound Bi_2Te_3 had the highest *p*-type conductivity, Bi_2Te_2Se the lowest conductivity, and Bi_2Se_3 the highest *n*-type conductivity. The relationship between Seebeck coefficient and electrical conductivity was found to resemble the Price Loop configuration. *C*-values for the selenium-rich half of the system were calculated to be constant, indicating conduction predominantly by one type of carrier. The *p*–*n* transition and reversal of property trends at Bi_2Te_2Se coincided with the position, previously proposed, of total occupation of the Te^2 atom sites by selenium. K_T–K_{el} curve having two minima was obtained. These minima coincided closely with compositions for which maximum lattice distortion may be expected through preferential occupation of Te^2 sites by selenium.

INTRODUCTION

Previous X-ray analyses [1–3] indicate the Bi_2Te_3–Bi_2Se_3 system to consist of a continuous series of isomorphic (rhom.) $Bi_2Te_{(3-x)}Se_x$ compounds. The thermoelectric properties of such compounds make an interesting study, since the mode of conduction changes from *p*–*n* with increasing values of *x*. Of added interest is the apparent existence of two types of tellurium sites and the proposed preference of one of these sites for selenium.

EXPERIMENTAL PROCEDURES

Preparation of compounds

The bismuth, tellurium, and selenium used in this investigation were obtained from the American Smelting and Refining Company and were of 99·999 per cent purity. Prior to compounding, the individual elements were melted in Vycor under dynamic vacuum to reduce the concentration of gaseous impurities and to effect physical consolidation. After being weighed on a standard analytical balance, the constituents were loaded into Vycor capsules having a 10 mm i.d. upper section and a 7 mm i.d. nose section. Such design, together with the pre-melting described above, permitted compact loading, decreased the volume of occluded space, and minimized disproportioning due to differential vapor pressures. The charged capsules were evacuated to pressures less than 0·05 μ of Hg and sealed. Extreme caution was used throughout to avoid contamination.

Melting was conducted at 750–870°C for 30 min in a resistor-wound tube furnace. Concurrently, the longitudinal axes of the furnace and capsule were oscillated slowly through an angle of about 15° on either side of horizontal to promote homogeneity. Transfer to a Bridgman furnace was performed by rapidly drawing the capsule upward from the melting furnace into the Bridgman. Normal freezing was obtained by lowering from the hot chamber (~650°C) into an ice-cooled chamber at a rate of 10 mm per hr.

Physical measurements

All measurements were made on cylindrical samples of 7 mm dia.

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Prior to sectioning, electrical resistivities were obtained at five predetermined stations along the ingots. A modified four-probe method was used with two sets of flexible copper slings substituted for the point probes. A direct current of 0·2–1·0 amp was supplied by slings at the ends of the ingot and the potential drop across slings (spaced 1·0 cm apart and centered at the 5 positions) was measured on a Kintel microvoltmeter.

Seebeck coefficients were determined on cylindrical samples 1·2 cm long. A sample was placed uniaxially between copper electrodes, maintained at a 10·0 $\pm$ 0·1°C differential, and the e.m.f. generated was measured with reference to copper.

The thermal conductivity apparatus used was as follows: A cylindrical sample was placed uniaxially in thermal contact with a cylindrical heater (copper, wound with No. 40 manganin wire) and with a cyclindrical copper heat-sink. The heater-sample-sink column (7 mm dia.) was mounted above a Dewar, with the lower end of the sink immersed in ice water. By means of a Plexiglas cover, a dead-air space was maintained around the column. Number 40 chromel–alumel thermocouples were embedded in the copper heater and sink, immediately adjacent to the copper-sample interfaces. A thermocouple was positioned in proximity to, but not touching, the heater to measure ambient temperature. By means of a four-pole two-gang switch, the hot and cold junction temperatures and the hot junction-ambient differential temperature were readily obtained.

In measuring thermal conductivity, the power input to the heater was adjusted so that the hot junction-ambient differential temperature was zero. At this thermal equilibrium point, heater power input and temperatures of hot and cold junctions were recorded. Thermal conductivity was calculated from $\kappa = (W/\Delta T)\,(L/A)$, where W is the electrical power input, ΔT is the temperature differential across the sample, and L/A is the sample length-to-area ratio. Using this method, reproducibility of κ values was found to be within $\pm$5 per cent. The inherent error of the method is believed to result in κ values slightly lower than the true values. A similar apparatus has been described recently by Downing [4].

RESULTS AND DISCUSSION

Electrical conductivity and Seebeck coefficient

Compositions investigated are listed in Table 1, together with corresponding experimental and calculated data for 300°K. Compounds defined by $0 \leqq x < 1$ were *p*-type. Compounds (Table 1) defined by $1 < x \leqq 3$ were *n*-type. At the composition $x = 1$, both *p*- and *n*-conduction were observed within the same sample. For this, as well as for closely bordering compositions, it is apparent that local inhomogeneities can result in relatively large variances of thermal e.m.f., since the latter values change markedly with small changes in composition.

Electrical conductivity decreased monotonically from 729 Ω^{-1} cm^{-1} at $x = 0$ (Bi_2Te_3). to a minimum of 84 Ω^{-1} cm^{-1} at $x = 1{\cdot}0$ ($Bi_2Te_2Se_1$), and then increased monotonically to 1953 Ω^{-1} cm^{-1} at $x = 3{\cdot}0$ (Bi_2Se_3). These data support those of Austin and Sheard [1] who determined that optical energy gap increased linearly from 0·15 eV at $x = 0$ and reached a maximum of 0·31 eV at $x = 0{\cdot}9$, at which composition a sharp change of slope occurred. With higher values of x, the energy gap was found to decrease gradually to 0·28 eV at $x = 3{\cdot}0$.

Seebeck coefficient data are plotted as a function of the logarithm of electrical conductivity in Fig. 1. The resulting curve approximates the Price Loop [5] configuration. Using the equation $S = (k/e)\,(C - \ln\sigma)$, values for C were calculated as listed in Table 1, A C-value of 9·0 was determined at both $x = 0$ and 0·15. A C-value of 8·3 was determined for the selenium-rich compounds defined by $x = 1{\cdot}5$, 1·8, 2·0, 2·33, and 3·0. In these,

TABLE 1. THERMOELECTRIC PROPERTIES OF $Bi_2Te_{(3-x)}Se_x$ COMPOUNDS AT 300°K

Composition		S, (μV/°C)	σ (Ω^{-1} cm^{-1})	C value*	Thermal conductivity (mW/cm °C)			Z, °C^{-1} $\times 10^3$
Mol% Bi_2Se_3 (bal. Bi_2Te_3)	x (in $Bi_2Te_{(3-x)}Se_x$)				κ_T	κ_{el}	$\kappa_T - \kappa_{el}$	
0	0·00	212 (*p*)	729	9·04	19·8	3·3	16·5	1·66
5	0·15	231 (*p*)	591	9·05	16·1	2·7	13·4	1·96
10	0·30	273 (*p*)	290	†	13·1	1·3	11·8	1·65
16·67	0·50	290 (*p*)	206	†	11·9	0·9	11·0	1·46
20	0·60	284 (*p*)	180	†	12·0	0·8	11·2	1·20
33·33	1·00	~0	84	†	15·6	0·4	15·2	0
50	1·50	228 (*n*)	315	8·38	14·4	1·4	13·0	1·14
60	1·80	180 (*n*)	513	8·32	13·0	2·3	10·7	1·28
66·67	2·00	135 (*n*)	833	8·28	14·5	3·8	10·7	1·05
77·78	2·33	109 (*n*)	1182	8·33	17·5	5·3	12·2	0·80
100	3·00	70 (*n*)	1953	8·39	27·0	8·8	18·2	0·35

* Calculated from $S = k/e\,(C - \ln\sigma)$.
† Inconstant C values.

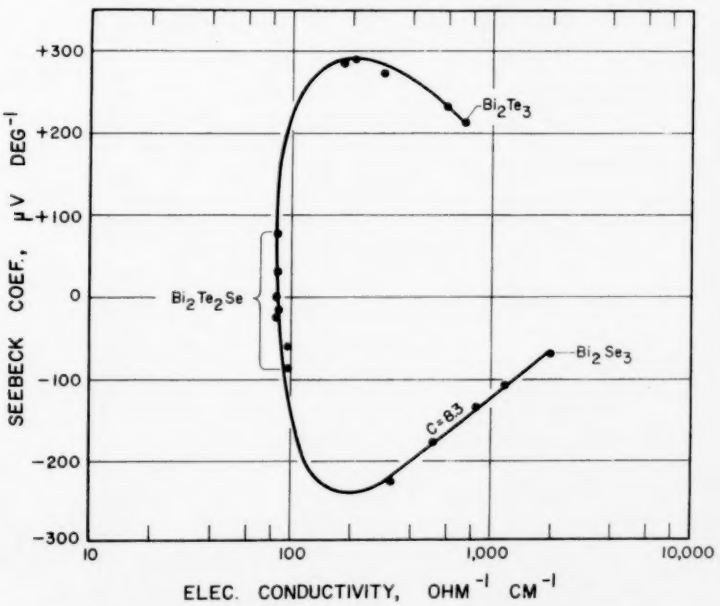

FIG. 1. Relationship between seebeck coefficient and electrical conductivity for $Bi_2Te_{(3-x)}Se_x$ compounds at 300°K.

conduction is predominantly by electrons. Conduction for intermediate compositions of inconstant C is by mixed carriers. Assuming [6] that $C = A + \ln 2(2\pi m^* kT/h^2)^{3/2} e\mu$, where A is a factor containing the scattering parameter, m^* the effective mass and μ the mobility, then equal values of C are significant also in indicating equivalent scattering

parameters, effective mass, and mobility of carriers. This would appear to hold true in the selenium-rich half of the Bi_2Te_3–Bi_2Se_3 system.

Relation of electrical conduction to structure

Several papers [7–10] have been published concerning the atomic arrangement and chemical bonding of bismuth telluride. A simplified atom model of bismuth telluride is shown in Fig. 2. Drabble and Goodman [10] (based on observations of Austin and Sheard [1]) hypothesized that, upon substitution, selenium atoms first enter Te^2 sites. When the Te^2 sites are occupied completely, they concluded that selenium then enters Te^1 sites.

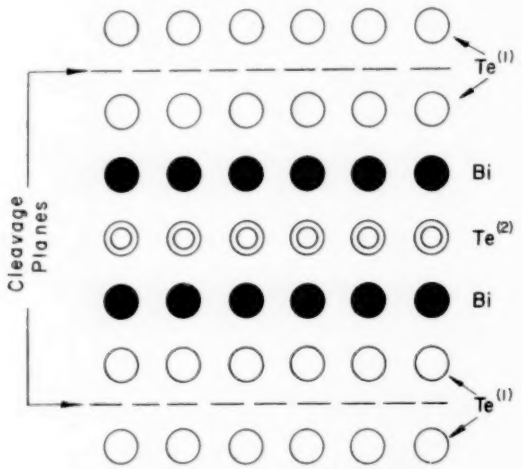

FIG. 2. Arrangement of atoms in bismuth telluride as viewed parallel to basal plane, showing layer structure and two types of tellurium atoms.

Considering the transition from Bi_2Te_3 to Bi_2Se_3 in light of the preferential-substitution hypothesis, Bi_2Te_3 has the highest *p*-type conductivity in the system. Then, with initial substitution of selenium in Te^2 sites, Bi–Te^2 pair bonds would be replaced by more ionic Bi–Se^2 bonds. Here decreasing electrical conductivity and increasing energy gap [1] were noted. At $x = 1$, the Bi–Te^2 pair bonds hypothetically would be replaced by Bi–Se^2 bonds and the solid would consist of mutually-bonded Te^1–Bi–Se^2–Bi–Te^1 chains. At Bi_2Te_2Se the Seebeck coefficient is observed to cross zero, electrical conductivity is minimum, and energy gap is essentially maximum. With continued selenium substitution (now in Te^1 sites) the observed property trends are reversed, i.e., the sign of the Seebeck coefficient becomes negative, electrical conductivity increases, and energy gap decreases slightly.

Thermal conductivity

Thermal conductivity data are listed in Table 1 and plotted in Fig. 3. The electronic component of thermal conductivity was calculated from $\kappa_{el} = (5/2 + \nu)\ (k/e)^2 T\sigma$, with $\nu = -1/2$ assumed for non-degeneracy and lattice scattering. Values for $\kappa_T - \kappa_{el}$ were found to decrease continuously from 16·5 mW/cm°C at $x = 0$ (Bi_2Te_3), to a valley of 11·0 mW units at $x = 0{\cdot}5$, increase to an intermediate maximum of 15·2 mW units at $x = 1$

(Bi_2Te_2Se), decrease again to a valley of 10·6 mW units at $x \cong 1{\cdot}9$, and finally increase to a terminal high of 18·2 mW units at $x = 3{\cdot}0$ (Bi_2Se_3).

The double-minima curves of Fig. 3 merit careful consideration. Rosi and co-workers [11], using *n*-type CuBr-doped samples, obtained an intermediate κ_{ph} rise with a maximum point at $x = 1{\cdot}5$. On the other hand, Birkholtz [3], using *n*-type AgI-doped samples, obtained a smooth κ_{ph} curve with a minimum at $x \cong 0{\cdot}6$.

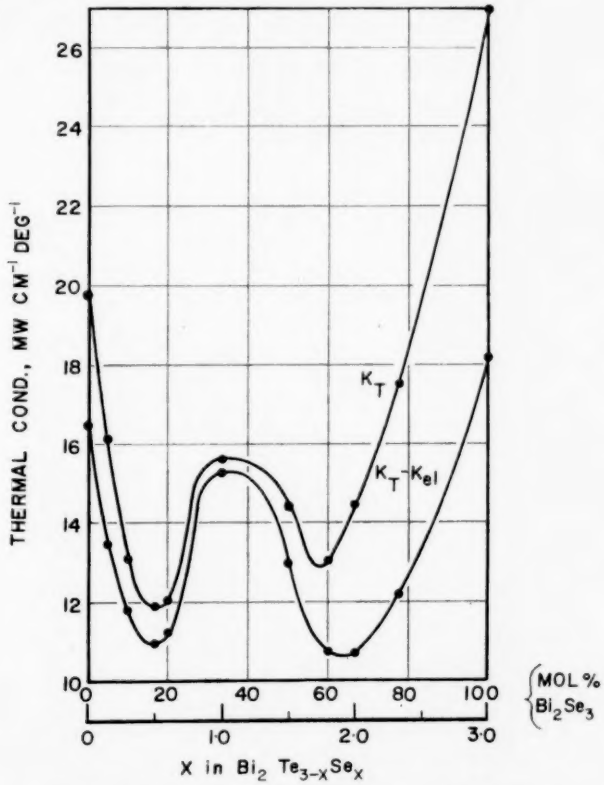

FIG. 3. Thermal conductivity of the Bi_2Te_3–Bi_2Se_3 system.

Interpretation of Fig. 3 requires consideration of both the ambipolar contribution to the thermal conductivity and the preferential substitution hypothesis [10]. If the intrinsic condition and an energy gap of 0·30 eV [1] are assumed for Bi_2Te_2Se (where Seebeck coefficient ~ 0), the maximum theoretical κ_{amb} according to Price equations [12] is 11·5 mW/cm °C. Thus, where $\sigma_n = \sigma_p$ and at bordering compositions, κ_{amb} can be appreciable. Conjunctively, the $\kappa_T - \kappa_{el}$ minima observed at $x = 0{\cdot}5$ and 1·9 coincide closely with compositions in which, based on preferential substitution, Se = Te in Te^2 and in Te^1 atom sites, respectively.

CONCLUSIONS

Eleven undoped $Bi_2Te_{(3-x)}Se_x$ compositions over the range $0 \leqslant x \leqslant 3$ were prepared and measured. A smooth electrical conductivity curve was obtained, with high values at the system terminals and a minimum value at Bi_2Te_2Se. At this composition, a near-maximum

energy gap was reported [1] and Seebeck coefficient crossed zero. The *p*-to-*n* transition and reversal of property trends at Bi_2Te_2Se coincide with the position of total occupation of Te^2 atom sites by selenium, previously proposed [10]. A double-minima $\kappa_T - \kappa_{el}$ curve was obtained, which minima coincide closely with compositions for which maximum lattice distortion may be expected through preferential occupation of Te^2 sites by selenium.

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THE FORMATION OF TERNARY SEMICONDUCTING ALLOYS*

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ABSTRACT

TO DATE the synthesis of ternary semiconducting materials has been limited generally to alloys of isomorphous, isovalent compounds, e.g., PbTe–PbSe, Bi_2Te_3–Sb_2Te_3, InAs–InP, and to the replacement of the cation of a binary compound by a combination of cations with the same net valence, e.g. $CdSnAs_2$ from InAs, $AgInTe_2$ from CdTe. These materials may all be regarded as electronically neutral derivatives of the parent binary compounds. It is not generally recognized, however, that there are three other mechanisms by which ternary or higher-component semiconducting materials may be synthesized. Thus, four classes of semiconducting alloys may be distinguished:

I. Alloys of isomorphous, isovalent compounds.
II. Alloys of anisomorphous, isovalent compounds.
III. Alloys of isomorphous, anisovalent compounds.
IV. Alloys of anisomorphous, anisovalent compounds

Examples of Class I alloys are given above. Examples of Class II alloys should be obtained in such systems as Bi_2Te_3–As_2Te_3, HgSe–CdSe, PbTe–GeTe, and Sb_2Te_3–Sb_2Se_3; in each case partial solubility should occur although the crystal structures of the individual compounds differ. Examples of Class III would be CdTe–InSb pseudobinary alloys where the structures are identical but the valences of both the cations and the anions differ, and InAs–$CdSnAs_2$, where the anion sub-lattices are identical but the structures and valences of the cations differ.

Examples of Class IV alloys are solid solutions of the composition, $(PbTe)_{0.9}$ $(CdTe)_{0.1}$, $(PbTe)_{0.93}$ $(InTe)_{0.07}$, and $(Bi_2Te_3)_{0.75}$ $(In_2Te_3)_{0.25}$, in which both the cation valences and the structure of the individual compounds differ. Single crystals of these compositions have been prepared with the structure type characteristic of pure PbTe and Bi_2Te_3, in which the thermoelectric properties differ markedly from those of the pure binary compounds, but the free charge carrier concentrations are virtually unchanged. These surprising results are due evidently to the promotion of the *s*-orbital in the valence shell of the impurity atom, under the combined influence of the octahedral crystal field and contraction of the lattice, to a level in the conduction band. It is believed that this phenomenon is of general occurrence in octahedrally coordinated semiconductors. It suggests that the cation-to-anion ratio in compounds such as Bi_2Te_3, may be substantially reduced with electronic compensation being achieved by the promotion of some of the remaining cations to a pentavalent state.

* A complete discussion of this work will be published in an early issue of this journal.

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THERMOELECTRIC PROPERTIES OF Ag_2Te AND Ag_2Se

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INTRODUCTION

IT HAS been shown by Goldsmid [1] that the optimised thermoelectric figure of merit, Z, is proportional to

$$\frac{m^{*3/2}\,\mu}{\kappa_{ph}}$$

where m^* = carrier effective mass ratio; μ = carrier mobility; and κ_{ph} = lattice component of the thermal conductivity.

This expression assists us in the search for improved thermoelectric materials, in that it is expressed in terms of basic material parameters. Goldsmid [1] further showed that μ/κ generally increases in compounds made from the heavier elements. This, together with the earlier work of Faust and Ridgley [2] and Appel [3] on Ag_2Te, led us to investigate in more detail the thermoelectric properties of silver telluride and selenide.

MATERIAL PREPARATION AND MEASUREMENT TECHNIQUES

The preparation of the materials, and the measurement of Hall effect, Seebeck coefficient, electrical and thermal conductivities, were carried out using techniques described elsewhere [4, 5].

RESULTS

All measurements were made on polycrystalline material. The low-temperature phases of Ag_2Te and Ag_2Se are of orthorhombic structure. In the range 100°C to 130°C both undergo phase changes to the cubic form. These changes in phase introduce difficulties in the growth of single crystals; crystals larger than a few mm^3 were not obtained. However, due to the small energy gap, the electrical properties are not greatly affected by crystal size.

In the temperature range 55°K to 300°K both Ag_2Te and Ag_2Se are n-type. By introducing excess tellurium Ag_2Te could be made p-type at low temperatures. On increasing the tellurium content to about 3 atomic per cent excess, the compound becomes p-type over the entire temperature range studied [6], but the structure changes to the hexagonal form of $Ag_{(2-x)}Te$. Attempts to make p-type Ag_2Se by stochiometric deviations and impurity doping (arsenic, antimony or silicon) were not successful. Small quantities of AgI of the order of 10^{19} atoms/cm^3 increased the concentration of donor impurities in Ag_2Te. Hence it appeared early in this study that for room temperature applications both Ag_2Te and Ag_2Se would be useful only as n-type thermoelectric materials.

The thermoelectric figure of merit at room temperature was calculated for a range of electrical conductivities and the results for Ag_2Te are shown in Fig. 1. The highest observed

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value for Ag_2Te was $1{\cdot}3 \times 10^{-3}$ °C^{-1}, corresponding to a Seebeck coefficient of -129 μV/°C, electrical resistivity of $1{\cdot}0 \times 10^{-3}$ ohm-cm and thermal conductivity of $1{\cdot}25 \times 10^{-2}$ Wcm^{-1} °C^{-1}. The work on Ag_2Se was less extensive, such that curves corresponding to those shown in Fig. 1 could not be drawn. However, the highest figure of merit observed

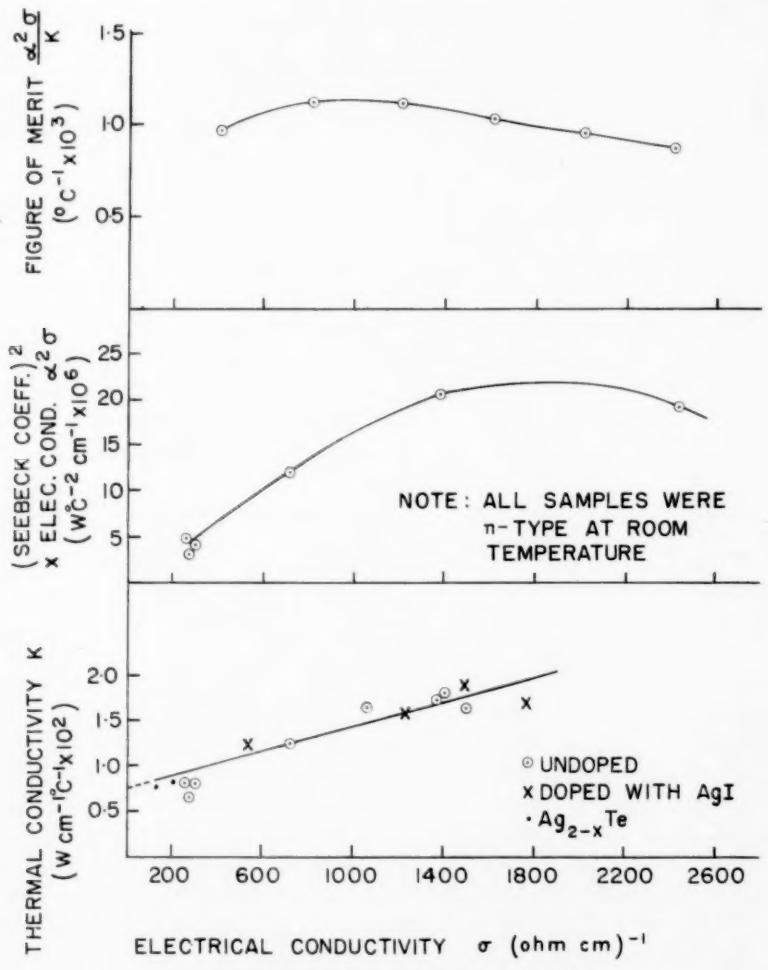

FIG. 1. Thermoelectric properties of Ag_2Te.

in Ag_2Se was $2{\cdot}3 \times 10^{-3}$ °C^{-1} corresponding to a Seebeck coefficient of -148 μV/°C, electrical resistivity of $0{\cdot}73 \times 10^{-3}$ ohm-cm and thermal conductivity of $1{\cdot}31 \times 10^{-2}$ W-cm^{-1} °C^{-1}.

The values observed for the Seebeck coefficient at the maximum figure of merit did not correspond to the anticipated values given by

$$\alpha_{opt} = 2\frac{k}{e}\left(1 + \frac{\kappa_{el}}{\kappa_{ph}}\right) \tag{1}$$

as derived by Joffé [7], where α_{opt} = optimized Seebeck coefficient; κ_{el} = electronic contribution to the thermal conductivity; κ_{ph} = lattice contribution to the thermal conductivity: and

$$\frac{k}{e} = \frac{\text{Boltzmann constant}}{\text{electronic charge}} = 86\ \mu\text{V/°C}.$$

This expression assumes the presence of free charge carriers of one sign only. Hall-effect measurements as a function of temperature (see Figs. 2 and 3) show that both Ag_2Te and Ag_2Se have extremely small forbidden energy gaps, and high electron mobilities ~10,000

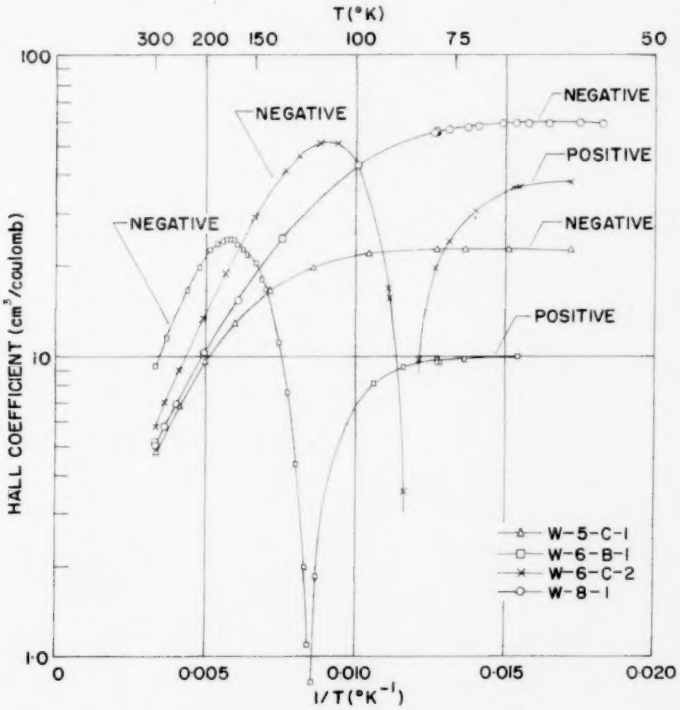

FIG. 2. Hall constants in Ag_2Te.

and 2000 cm²/V-sec, respectively, at room temperature. The exact values of the energy gaps are difficult to determine due to the compounds' being degenerate over the whole temperature range [4], but appear to be of the order of 0·05 eV at absolute zero. In the case of Ag_2Te the carrier mobility ratio appears to be sufficiently low such that the contribution of holes to the Seebeck coefficient cannot be neglected. However, the situation appears to be different in Ag_2Se. The Hall effect curves for the two specimens of Ag_2Se, shown in Fig. 3, were replotted assuming that the mobility ratio was large. In such a case the Hall constant (R) is given by

$$R = \frac{c}{e}\frac{nb^2 - p}{(nb + p)^2} = \frac{c}{e(n_i + N_d)} \tag{2}$$

Where c = scattering constant (assumed = 1); n_i = intrinsic carrier concentration; N_d = donor impurity concentration, obtained from the extrinsic Hall constant.

On plotting

$$\log\left[\left(\frac{1}{Re} - N_d\right) T^{-3/2}\right] \text{ versus } \frac{1}{T}$$

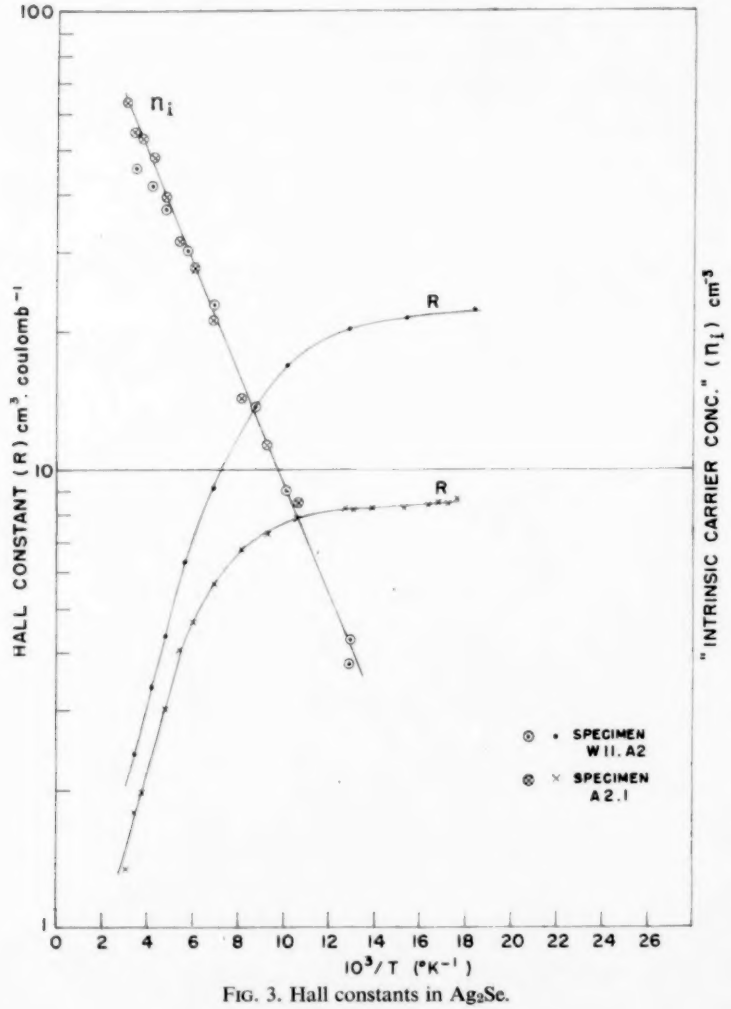

FIG. 3. Hall constants in Ag_2Se.

the curves for the two specimens coincided, supporting the assumption of a large mobility ratio.* Although in fact higher values for the Seebeck coefficient were obtained in Ag_2Se than in Ag_2Te, they were still lower than the thermoelectric optimum given by equation (1). This is due to a high degree of degeneracy in Ag_2Se. Calculations of the effective mass

* The slope of this plot gave a value for the forbidden energy gap of 0·05 eV. From the slope of log R vs. $1/T$ a value of 0·075 eV was obtained, in agreement with the results of Busch and Junod [8], however, this calculation ignores the temperature variation of the density of states term in the expression for conductivity.

(m_e/m_0) and Fermi level, ξ, from the room temperature values of Hall constant and Seebeck coefficient, assuming b to be very large and lattice scattering to be predominant, support this viewpoint. The values obtained were $m_e/m_0 = 0{\cdot}1$ and $\xi = 3\,kT$ above the conduction band edge.

The relationship between the thermal and electrical conductivity for Ag_2Te appeared to be linear giving a Lorentz number of $3{\cdot}12\ (k/e)^2$ (close to the theoretical value of $\pi^2/3(k/e)^2$ for a degenerate semiconductor) and a lattice thermal conductivity of $0{\cdot}72 \times 10^{-2}$ Wcm^{-1} °C^{-1}. The lattice thermal conductivity in Ag_2Se appeared to be of the same order as Ag_2Te and consequently it appeared worthwhile to investigate solid solutions of Ag_2Te and Ag_2Se.

A study of these solid solutions indicated a minimum lattice thermal conductivity of about $0{\cdot}5 \times 10^{-2}$ Wcm^{-1} °C^{-1} for the compositions 40 mol per cent Ag_2Te, 60 mol per cent Ag_2Se, assuming non-degeneracy. However, the ratio μ/κ_{ph} deteriorated in these solid solutions and consequently no enchancement in the figure of merit was obtained.

CONCLUSIONS

Ag_2Te and Ag_2Se do not appear to be competitive with the bismuth–antimony–tellurium–selenium, system for room-temperature cooling applications. At low temperatures, in the extrinsic conductivity range where carriers of one sign only would contribute to the Seebeck coefficient, and where the mobility will be increased, higher figures of merit may be realized. Seebeck coefficients as high as $-160\ \mu$V/°C, and electron mobilities as high as 20,000 cm^2/V sec, have been obtained [4] at 77°K.

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THE SYNTHESIS, STRUCTURE AND THERMOELECTRIC PROPERTIES OF SOME II–IV COMPOUNDS*

VIRGINIA A. RUSSELL† and PHILIPP H. KLEIN‡

ABSTRACT

COMPOUNDS of alkaline-earth metals with silicon, tin, and lead have been prepared and their crystal structure and thermoelectric properties determined. Because of the reactivity of the alkaline-earth metals and their high vapor pressures at the temperatures required for synthesis, special handling techniques were evolved. X-ray data showed slight deviations from a cubic structure, in most cases, in agreement with the sparsely published structural information. The figure of merit (at room temperature) of Ca_2Pb (with 1 mol per cent added Ca) was $0{\cdot}68 \times 10^{-3}\,(^{\circ}K)^{-1}$, more than an order of magnitude greater than that of undoped or lead-rich material. Preliminary measurements on Ca_2Sn, Ba_2Pb, Ba_2Sn, Sr_2Sn, and Sr_2Si indicate room temperature figures of merit for these materials in the range 10^{-5} to $10^{-4}\,(^{\circ}K)^{-1}$.

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* A more complete discussion of this work will be published at a later date.
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THERMOELECTRIC PROPERTIES OF SOME CHALCOPYRITE-TYPE COMPOUNDS*

R. BOBONE, L. F. KENDALL and R. H. VOUGHT†

ABSTRACT

WORK on some I III VI_2 compounds having the chalcopyrite structure will be discussed. $AgGaS_2$, $CuGaS_2$, $AgGaSe_2$, $CuGaSe_2$, $AgGaTe_2$ and $CuGaTe_2$ were prepared and values of Seebeck coefficient, electrical resistivity, and thermal conductivity were measured. $CuGaTe_2$ showed the most promising thermoelectric properties with room temperature values of $S = 128\ \mu V/°C$, $\rho = 4{\cdot}1 \times 10^{-3}\ \Omega$-cm, $\kappa = 0{\cdot}022$ W/cm °C.

Studies of the effects of environment and heat treatment and of the resulting thermoelectric properties at high temperature have been made. Results of these studies will be presented.

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† General Electric Company, Schenectady, New York.

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SEMICONDUCTOR MATERIALS FOR THERMOELECTRIC POWER GENERATION*

F. D. Rosi, E. F. Hockings and N. E. Lindenblad†

ABSTRACT

A general consideration of the thermoelectric properties of semiconductors suggests that (1) this class of materials can be useful in power generating thermocouples operating at least up to 700°C, and (2) construction of thermocouple branches in a sandwich-type arrangement, or by graded alloying, will be necessary to achieve high figures of merit over a wide temperature range and, hence, high power-generating efficiencies. A large number of ternary compound semiconductors having the cubic structure were synthesized; and those, such as $AgSbTe_2$, with the rock-salt structure are characterized by low lattice thermal conductivities ($<0{\cdot}0075$ W cm^{-1} deg^{-1}). The lattice thermal conductivity as a function of composition was examined in the alloy systems of $AgSbTe_2$ with PbTe, SnTe and GeTe. The minimum in the lattice thermal conductivity for the $AgSbTe_2$–PbTe system gives an effective "mean free path" for phonons which is less than unit-cell dimensions. Measurements of the temperature dependence of thermoelectric properties on a number of solid solution alloy systems showed that (1) solid solution alloys of Bi_2Te_3 with Bi_2Se_3, Sb_2Te_3 and Sb_2Se_3 provided the best *p*- and *n*-type material for thermocouple operation in the temperature range 25°C–250°C, (2) the ternary compound, $AgSbTe_2$ and its alloys with GeTe provided the best *p*-type material for the range, 250°C–550°C, and (3) alloys in the PbTe–SnTe system provided the best *n*-type material for the range, 250°–550°C. Power generating thermocouples, constructed in the sandwich-type arrangement of materials, provided an efficiency of 10–12 per cent on operating over the temperature range, 20°C–550°C; i.e., a T_H–T_C = 530°C. Continuous thermocouple operation for 300 hr resulted in no significant deterioration of material properties.

* The complete text of this paper appeared in *RCA Rev.* **22**, March, 1961. The abstract is reproduced here by permission of *RCA Review*, RCA Laboratories, Princeton, New Jersey.

† RCA Laboratories, Princeton, N.J.

SESSION IV

SYNTHESIS AND EVALUATION OF MATERIALS (B)

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A STUDY OF SUBSTITUTED MnTe*

A. J. Panson†

ABSTRACT

MnTe has been doped with Li or Na according to the following reaction:

$$\frac{x}{2}\,Li_2Te + (1 - x)\,MnTe + \frac{x}{2}\,Te = Li_xMn_{(1-x)}Te.$$

Powder metallurgy techniques were employed. The Li_2Te or Na_2Te used was prepared by reacting Te with the alkali metal dissolved in liquid ammonia.

The solubility limits of the dopants were determined by plotting the Seebeck coefficients as a function of log of the dopant concentration. The solubility limit of Li was found to be $x = 0{\cdot}06$.

Electrical properties of these materials have been studied as a function of temperature up to 1025°C.

Compounds were also made with Se substituted for Te according to the following formulas:

$$Na_x\,Mn_{(1-x)}Te_{(1-y)}Se_y$$

$$Li_x\,Mn_{(1-x)}Te_{(1-y)}Se_y$$

Their electrical properties have been determined.

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† Westinghouse Research Laboratory, Pittsburgh, Pennsylvania.

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RARE EARTH SULFIDES AS HIGH-TEMPERATURE THERMOELECTRIC MATERIALS*

S. W. KURNICK, M. F. MERRIAM and R. L. FITZPATRICK†

Summary—The rare earth sulfides appear promising for use as high-temperature power conversion thermoelectric materials because of low lattice thermal conductivity and good chemical stability above 1000°C. We are making an intensive study of cerium sulfide, and to a lesser extent lanthanum sulfide and thorium sulfide, in the stoichiometric range in which these compounds are semiconducting. Some measurements have been made on barium sulfide–cerium sulfide solid solutions.

Electrical, optical, thermoelectric, and magnetic measurements have been made on crack-free cast samples of centimeter dimensions prepared by vacuum melting in molybdenum crucibles. Doping of the semiconductor by molybdenum is not believed to be serious, in view of the low Mo concentrations ($\sim$ 100 ppm or less) indicated by chemical analysis and of the high carrier concentrations measured. Measurements of the thermoelectric parameters have been made at elevated temperatures using small area contact techniques as well as more conventional methods. Values of $zT = 0{\cdot}3$ have been measured in cerium sulfide, without doping. Carrier concentration and Hall mobility have been measured by a simple and sensitive a.c. method. Mobilities measured to date in cerum sulfide are low ($\sim$ 1 cm^2/V-sec) and carrier concentrations are high (up to 10^{22}/cm^3) depending on the stoichiometry. Conduction mechanisms consistent with the data at hand are discussed.

INTRODUCTION

THE SELECTION of high-temperature semiconductor materials which can provide optimum thermal conversion efficiencies is a problem which must rely a great deal for its solution on experimental methods modified by some empirical rules. The selection of the semiconducting compound Ce–S‡ as such a thermoelectric candidate may best be understood from the work of previous investigators [1–7]. The two most important features of the compound as far as thermoelectric conversion is concerned are its high-temperature stability and low lattice thermal conductivity, which may be inferred from empirical relations [8]. The semiconductor is an electrical insulator at the Ce_2S_3 end of the composition range ($\sigma = 3 \times 10^{-9}$ mho/cm), but its conductivity increases with increasing cerium content, the Ce_3S_4 composition being semi-metallic ($\sigma = 3 \times 10^3$ mho/cm). This is a remarkably large range in conductivity for a single phase.

For a better understanding of the electrical and thermal transport mechanisms involved in this semiconductor, we have stressed three aspects in the intensive study of Ce–S:

1. The utilization of new techniques in thermoelectric measurements at high temperatures (800–1800°K):
   a. Measurements of the semiconductor efficiency parameter zT and the Seebeck potential α by a small area technique [9] to avoid radiation corrections.
   b. Measurements of the Hall effect to achieve better insight into the mechanism of conductivity and into the relative importance of mobilities and carrier concentration at different stoichiometries.
2. Metallurgical preparation of material by melting. This avoids certain disadvantages

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‡ The designation Ce–S is used to indicate the single phase of $CeS_{1{\cdot}33-1{\cdot}50}$ which has the Th_3P_4 structure.

inherent in sintered materials, such as atmospheric deterioration at room temperature. In addition, low-temperature heat treatments are characterized by mixed phases which are avoided by quenching from the melt [7].

3. Accumulation of data leading to an ultimate performance study of related semiconductors so as to apply the progress achieved on Ce–S to the problem of selecting materials from other rare earth sulfides (pure and doped) to obtain ultimate performance in temperature regions for which Ce–S alone is unsuitable.

Results to date indicate that qualitatively different transport mechanisms are dominant in different composition ranges. This work is not complete, but measurements to date already show promise, with directly measured zT values as high as 0·33. Values of zT synthesized from $\alpha^2\sigma$ measurements and assumed values of κ have been as large as 0·7. This places Ce–S in the role of a leading high-temperature thermoelectric candidate.

PREPARATION OF SAMPLES

All measurements have been made on cast material having 100 per cent of theoretical density. Porous Ce_2S_3, obtained by H_2S reduction of CeO_2 in the presence of carbon, is melted in vacuum in a molybdenum container at a temperature in the neighborhood of 2000 °C. Some loss of sulfur occurs during this process and the cast material has a composition intermediate between Ce_2S_3 and Ce_3S_4. Melting in graphite containers was found to be unsatisfactory; the cerium sulfide reacted with the graphite used. Tantalum is also attacked. With molybdenum, on the other hand, the casting usually separates cleanly the container after both have been cooled to room temperature. The appearance of the container wall indicates only slight attack, and chemical analysis indicates fairly low Mo concentrations (usually 100 p.p.m. or less) in the semiconductor. Melting is carried out in either an induction furnace (in which case a graphite susceptor is used to transfer power from the induction coil to the Mo boat) or in a resistance furnace (in which case the Mo crucible is suspended in the center of the helical graphite resistance element). After melting, the charge is cooled to room temperature over periods of 1–12 hr.

From the resulting cast material, slabs several centimeters in dimension are obtained free of cracks, as determined both visually and by electrical probing. It has proved possible to polish these slabs into blanks for optical measurements and to cut out samples for other physical measurements, using standard semiconductor techniques. The cast slabs and the samples cut from them are stable in air at room temperature. No changes in properties of either the surface or the bulk have been observed over periods of months. (An insulating layer, presumably an oxide, does, however, form on the surfaces of samples heated in air at 300 °C for a few minutes.)

The complex X-ray patterns characteristic of oxysulfides [4, 6] are not observed in melted material. The lower temperature phases of cerium sulfide [2, 5] are likewise absent, the pattern showing only the characteristic lines of the Th_3P_4 structure.

MEASUREMENTS

Electrical conductivity and Hall effect measurements at room temperature are performed by a.c. methods at 570 c/s. Conductivity is measured with the standard four-wire technique, the output from the potential probes being fed directly to a Hewlett–Packard wave analyzer (as a narrow band amplifier). The equipment for the Hall measurement, which is described more completely elsewhere [10], includes an impedance-matching trans-

former and a preamplifier between the sample and the wave analyzer. Signals can be detected down to noise levels of the order of 10^{-10} V. Low impedance leads and contacts are necessary. "Noiseless" magnetic fields of up to 5000 gauss are provided by permanent magnets.

Simultaneous measurements of electrical conductivity and Seebeck coefficient at temperatures from room temperature to 1600°C are obtained with the apparatus shown in Fig. 1. The temperature gradient existing in the furnace is used to generate the Seebeck

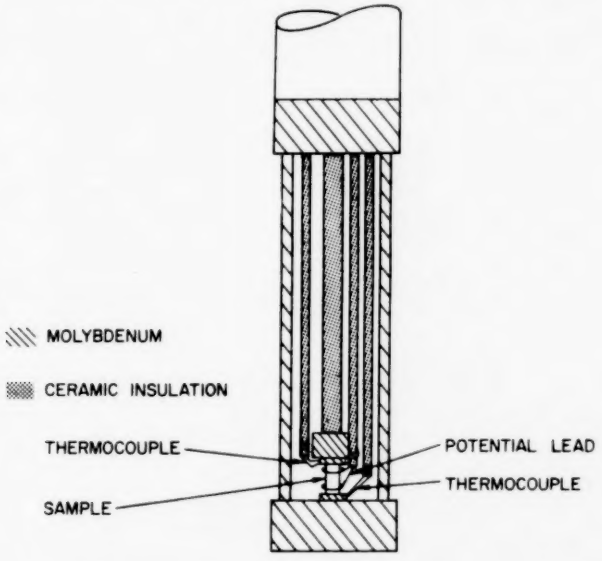

FIG. 1. Seebeck potential and conductivity fixture for small samples.

potential. Temperature-position profiles in an empty furnace indicate the actual temperature distribution in the sample is probably not far from the constant gradient assumed. The electrical conductivity is measured by a four-wire a.c. method similar to that used at room temperature.

The direct measurement of zT at various temperatures is accomplished with the small-area device developed by Cutler [9]. This device has the advantage that the thermoelectric performance parameter, $zT = (\alpha^2 \sigma \kappa^{-1})\, T$, is measured directly. Combination of measurements obtained on different samples is thereby avoided. It is possible to make measurements on small samples, or on samples with flaws. Another advantage of the method comes from the fact that, if the small-area contact is small enough, the measurements are insensitive to radiative heat transfer. The device is thus well suited to high-temperature measurements.

A direct current applied between the center wire and the outer can [9] causes the temperature of the center of the sample to rise above that of the more distant part, because both the Peltier heating and the Joule heating are more intense near the center. After a steady state has been established, the current is suddenly switched off. Since a temperature gradient exists between the center wire and the outer can, a transient thermoelectric voltage will appear between these two conductors, decaying to zero as the semiconductor comes to

thermal equilibrium. By measuring δV, the initial magnitude of the thermoelectric transient, and comparing with V, the voltage initially applied, the value of zT can be deduced, according to the equation

$$\frac{\delta V}{V} = \gamma + \frac{\gamma}{2\alpha T} V \qquad \text{where} \quad \gamma = \frac{zT}{1 + zT}.$$

In fact, by plotting $\delta V/V$ vs. V one can, in favorable cases, obtain both zT (from the intercept) and α (from the slope). This is illustrated in Fig. 2. Since the small-area device, as

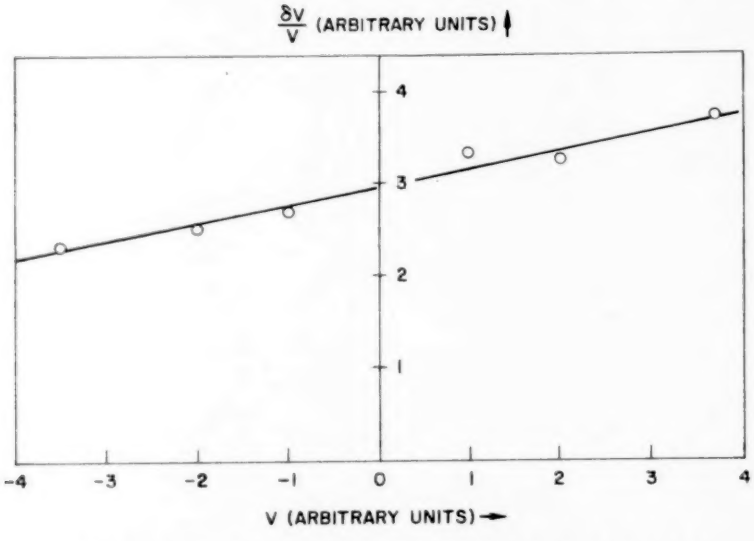

FIG. 2. Data from the small-area contact technique. zT is obtained from the intercept and α from the slope of the straight line.

applied in this laboratory, also includes potentiometric leads, the electrical conductivity is obtained concurrently with the zT and α measurement. The thermal conductivity can thus be obtained at high temperatures (up to 1600°C).

RESULTS AND DISCUSSION

The measurements to date are generally consistent with existing descriptions of the nature of cerium sulfide. There are, however, differences in detail. Physical understanding is still possible only in broad terms, though some progress has been made toward narrowing the range of possible models.

The Hall effect in compound semiconductors similar to cerium sulfide is usually small, and few measurements to date have been reported on this type of material. Consequently, theoretical interpretation has also lagged. It seems fairly certain, however, that a measured Hall voltage can be interpreted in terms of carrier mobility and carrier concentration. We have converted Hall voltages and conductivities to mobilities and carrier concentrations in the usual manner, ignoring any complications arising from large carrier concentrations and the possible presence of hopping processes. Room temperature Hall effect measurements are summarized in Table 1. They show high carrier concentrations, of the order of

10^{21}–10^{22} cm^{-3}, and low mobilities, of the order of 0·1–1 cm^2/V-sec. Although there is some scatter in the data, it appears that high conductivity is achieved both through higher carrier concentrations and through increased mobilities. All the material manufactured to date has been *n*-type.

The room-temperature electrical conductivity of samples prepared by melting has varied from a few mho/cm to a few thousand mho/cm. Because sulfur is lost in the high-

TABLE 1. HALL MEASUREMENTS

σ (mho-cm $^{-1}$)	Hall coefficient (cm^3 C^{-1})	*n* (carriers/cm^3)	μ (cm^2/V-sec)
100	$1·7\times10^{-3}$	$3·5\times10^{21}$	0·2
210	$0·85\times10^{-3}$	$7·4\times10^{21}$	0·2
900	$0·73\times10^{-3}$	$8·5\times10^{21}$	0·7
960	$1·5\times10^{-3}$	$4·0\times10^{21}$	1·4
1270	$1·1\times10^{-3}$	$6·0\times10^{21}$	1·4
2200	$1·65\times10^{-4}$	$3·8\times10^{22}$	0·4
2700	$4·2\times10^{-4}$	$1·5\times10^{22}$	1·1

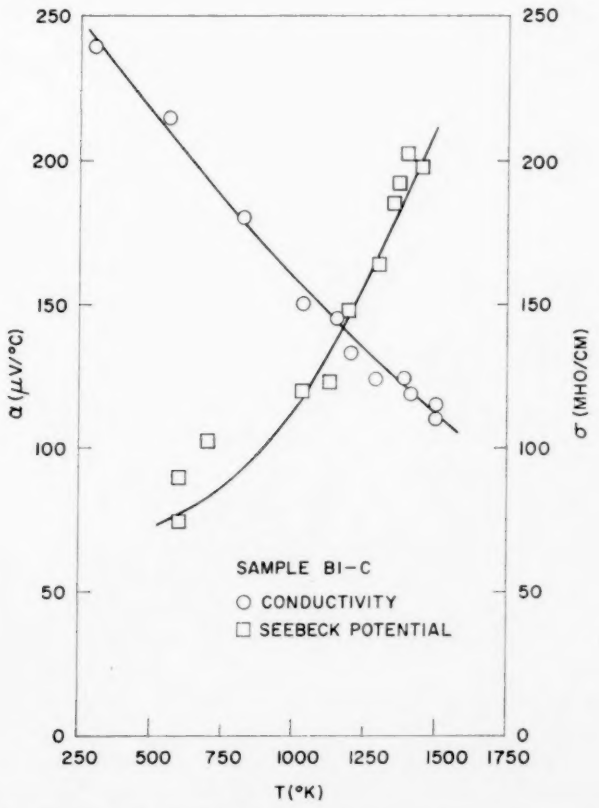

Fig. 3. Seebeck coefficient and conductivity as functions of temperature for undoped Ce-S sample.

temperature processing our samples receive, we would not expect to obtain very highly insulating material. (The only insulating samples with which we have worked so far were prepared by heat treating blanks in either sulfur or a hydrogen sulfide atmosphere.)

Our room temperature data are thus consistent with the usual interpretation of the conductivity transition from insulating Ce_2S_3 to high-conducting Ce_3S_4. In Ce_2S_3 the cerium ions are trivalent (Ce^{+++}). If to m "molecules" of Ce_2S_3 are added n "molecules" of CeS, in which cerium is divalent (Ce^{++}), resulting in $Ce_{(2+x)}S_{(3+x)}$ where $x = (n/m)$, there are x electrons per "molecule" which are less strongly bound than the valence electrons. These extra electrons provide electrical conductivity, and, as x approaches unity, result in

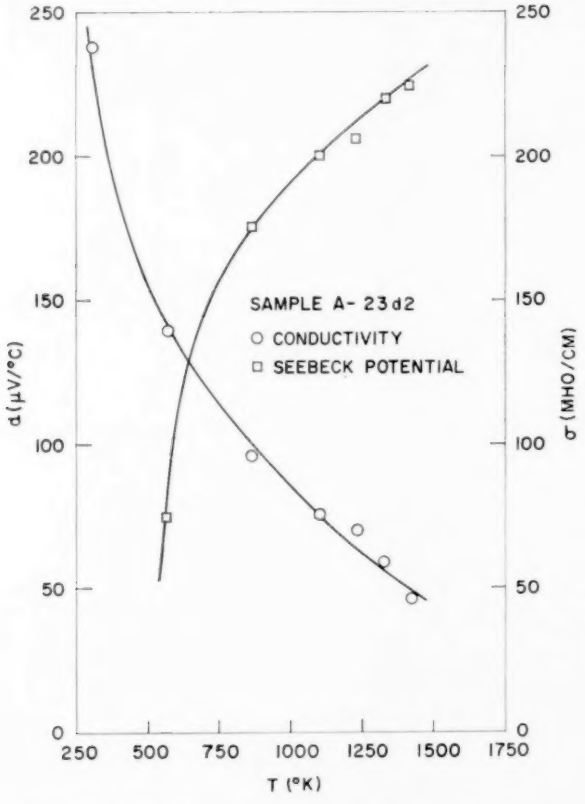

FIG. 4. Seebeck coefficient and conductivity as functions of temperature for highly-doped sample ($Ce_8BaS_{12.8}$).

the metallic bonding characteristic of Ce_3S_4. The question of whether these "extra" electrons are essentially free, or whether they form part of a more complex mobile entity, e.g., as polaron [11] is best left open at this time. It seems in any case likely that the applicability of any particular model will depend upon the value of x.

One might suppose that the high carrier concentrations and low mobilities found in the "metallic" Ce_3S_4 would render the transport properties in that material insensitive to doping. Such apparently is not the case. For example, when a sample of material having a conductivity of 1000 mho/cm was remelted in a general-purpose (and thus contaminated)

vacuum system and held above the melting point for several hours in an attempt to drive off any remaining sulfur, the room-temperature conductivity, instead of increasing, decreased to a value between 1 and 50 mho/cm, depending upon location in the ingot. Experience to date (perhaps half a dozen experiments) indicates that high-conductivity material is more sensitive to doping than is low-conductivity material. This is not, however, conclusively established. We note also that the data of Table 1 show less than perfect correlation between conductivity and the Hall effect. Correlation between bulk density (an index of stoichiometry [4]) and electrical conductivity is likewise not exact.

The behavior of α and σ as functions of temperature in a highly conducting sample is shown in Fig. 3. It is at once apparent that Ce_3S_4 is no ordinary metal. Both the magnitude and the temperature dependence of the Seebeck coefficient are more characteristic of a refractory ceramic insulator than of a metal.

The data of Fig. 3 yield $zT = 0{\cdot}7$ at 1500°K if a rather conservative value of 0·01 W/cm-°C is assumed for the thermal conductivity. This is a higher zT than has been reported to date for a material operating at this temperature. A rough measurement of zT with the small area technique on a less conducting material indicated, however, a maximum value of $zT = 0{\cdot}3$. We believe that this illustrates the danger of drawing conclusions from $\alpha^2\sigma$ data alone, particularly at high temperatures.

The effect of doping Ce–S with BaS has also been investigated. This study is not completed, but it appears that one effect of the BaS is to increase the rise in the Seebeck potential with the increase in temperature. Such an effect may lower the temperature at which maximum efficiency is attained. Data on a representative sample appear in Fig. 4.

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CONSIDERATIONS CONCERNING THERMOELECTRIC MATERIALS HAVING THE THORIUM PHOSPHIDE STRUCTURE*

F. L. CARTER†, R. C. MILLER† and F. M. RYAN‡

Summary—The Th_3P_4 structure has been reviewed and its relationship to the electrical properties of cerium sulfide has been discussed. Diluent doping is defined and its application to cerium sulfide (Th_3P_4 structure) is described.

INTRODUCTION

THE DIFFICULTIES in understanding as well as in discovering the high temperature thermoelectric properties of compounds having the thorium phosphide structure are now beginning to be appreciated by workers in the field. This is largely through efforts related to cerium sesquisulfide, although some other related rare earth compounds have received limited attention. We will consider four aspects of the general problem:

1. The thorium phosphide structure itself and the unusual adaptation of cerium sesquisulfide to this structure.
2. The concept of "diluent doping", a type of doping useful in enhancing electron mobility, and how it is related to the structure.
3. Some of the problems we met in the experimental determination of the thermoelectric properties along with the reliable high temperature results.
4. Finally, some considerations required in developing an adequate understanding of the electrical properties.

The high temperature phase (Th_3P_4 structure) of cerium sesquisulfide has a wide composition range varying from $x = 1{\cdot}5$ in the designation CeS_x to $x = 1{\cdot}33$. The former material, i.e., the sesquisulfide, is an insulator and has 1/9 of the metal sites vacant while for $x = 1{\cdot}33$ the phase has high conductivity (specific resistance is about 5×10^{-4} ohm cm) and corresponds to the structure in which all the metal sites are occupied [1, 2].

THE THORIUM PHOSPHIDE STRUCTURE

The Th_3P_4 structure is characteristic of several sulfides of the lanthanides and actinides and appears to be unique to those metals that have $4f$ or $5f$ orbitals available for bond formation. The structure is body-centered cubic with both kinds of atoms in special positions.

For the purposes of visualization the structure is best discussed first considering the metalloid atoms alone. These form strings of two kinds of tetrahedrons in the (100) direction. Both kinds of tetrahedrons have a single $\bar{4}$ axis of symmetry and possess two equal short edges and four longer edges. The larger of the tetrahedrons will be designated type *a* and the other type *b*. In the tetrahedron string these two types alternate and share short

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† Westinghouse Research Laboratories, Pittsburgh, Pennsylvania.
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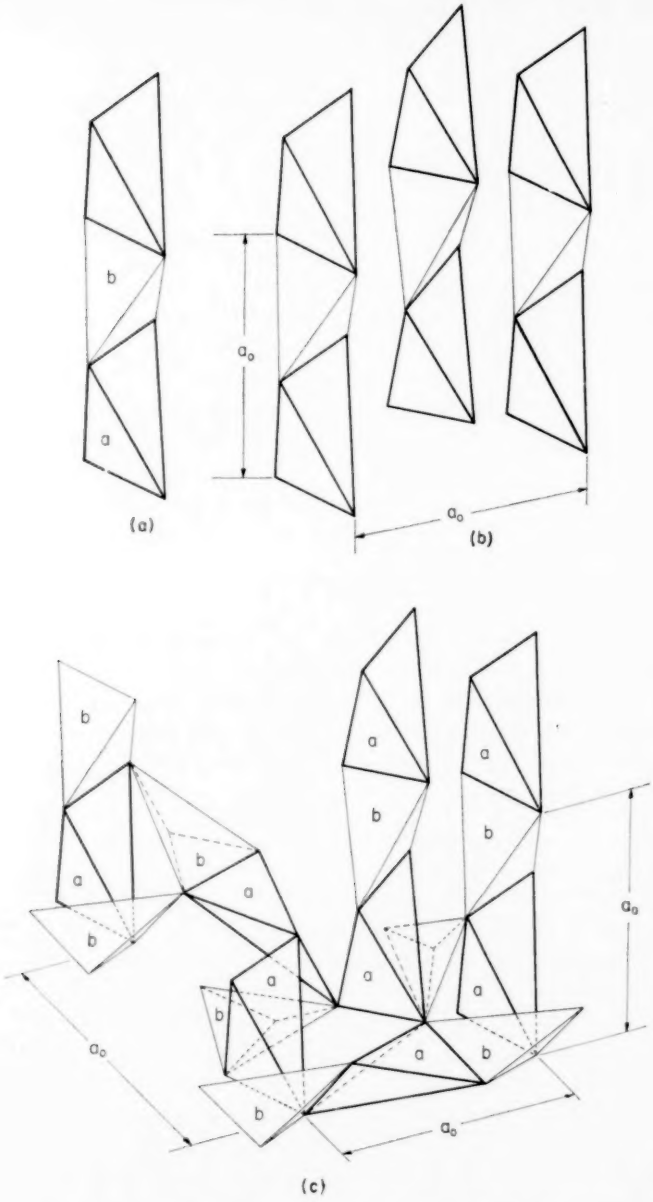

FIG. 1. Anion strings of tetrahedrons in the Th_3P_4 structure.

edges which are perpendicular to the (100) direction or $\bar{4}$ axis as shown in Fig. 1. Similar strings of anion tetrahedrons are found parallel to the other cell edges (i.e., in the other $\bar{4}$ directions). The three mutually perpendicular sets of strings are joined together into a three-dimensional anion array by sharing tetrahedron corners (Fig. 1(b) and 1(c)). Each anion is then shared in three different tetrahedron strings and accordingly is common to

three different *a* tetrahedrons as well as three *b* tetrahedrons. This method of viewing the Th_3P_4 structure is of considerable pedagogical aid but is not necessarily useful in discussing electrical properties.

In the filled structure (e.g., Ce_3S_4) the center of each of the larger tetrahedrons, i.e., type *a*, is the site of a cation. The smaller tetrahedrons are empty. The anion lies on the axis of a twisted trigonal prism formed by six cations. The top of the prism is rotated

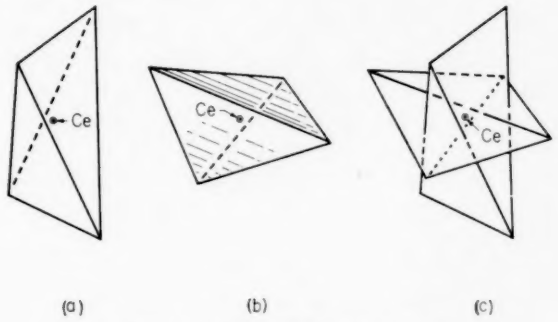

FIG. 2. Anion tetrahedrons about cerium in Ce_3S_4.

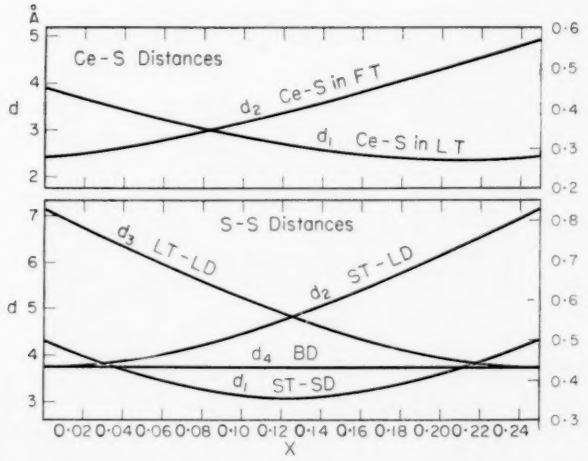

FIG. 3. Distances in Ce_2S_3 as a function of the anion parameter, *x*.

38° 13′ relative to the base. Figure 3 shows the two cation-anion distances d_1 and d_2 as a function of x, where x need be considered only in the range $0 \leqslant x < 0{\cdot}25$. If $x = 0{\cdot}083 \pm 0{\cdot}015$ (1/12) as reported by Zachariasen [2], we note that the two distances are equal. However, from a consideration of the anion-anion distances we see that this gives a closer contact than ionic radii would lead us to expect by about 0·46 Å. An examination of the structure indicates there are three anions near the top of the prism, each contingent to two of the cations of the top. Each of these three anions forms a close contact with the anion inside the "prism" when $x = 1/12$.

The cationic sites are at the centers of the type *a* anion tetrahedrons, as is consistent

with 4 symmetry. In addition to being circumscribed by this large and long anion tetrahedron, it is also at the centroid of a rather flat tetrahedron. Figures 2(a) and 2(b) show these two tetrahedrons and Fig. 2(c) indicates their relative relationship. The angle between the two top edges of the tetrahedrons perpendicular to the $\bar{4}$ axis is not quite 90° and varies with the value of x. The eight anionic near-neighbors about the cationic site form the corners of a dodecahedron which has two kinds of triangular faces. When $x = 1/12$ the two anion-cation distances are equal and each metal will have eight equal-distant metalloid neighbors. While for cerium sesquisulfide this arrangement gives excellent agreement with the calculated ionic radii sum of 2·97 Å compared with 2·98 Å, it gives a structure with short anion-anion contacts as discussed above. As x decreases from 1/12 the type *a* tetrahedron becomes longer and the flat tetrahedron becomes smaller and less flat.

Each metal has eight equal-distant metal neighbors in the filled structure. These are distributed between a long tetrahedron and a flat tetrahedron in a manner similar to the eight sulfur neighbors. In the case of Ce_2S_3 the metal–metal distance is about 4·04 Å.

The existence of the Th_3P_4 type structure seems to be dependent upon the ability of the metal to form simultaneously more than one tetrahedrally bonded structure. The availability of *f* orbitals in the lanthanides and actinides might be expected to permit this type of bonding. Other flat tetrahedral structures of the actinides are known [3].

If we apply formal valences in the discussion of Ce_3S_4 then we obtain a valence of $+2\frac{2}{3}$ for the cation, which might be considered as the average of $\frac{1}{3}$ of the metal atoms with a $+2$ valence and the rest trivalent. As one approaches the composition of Ce_2S_3 the number of formally divalent atoms becomes zero. Density considerations [4] show that in Ce_2S_3 1/9 of the metallic sites are vacant, or of the 12 *a* sites only $10\frac{2}{3}$ of them are filled. At this composition the formal valency of the cerium would be $+3$. It is to be expected that these vacancies are not randomly distributed as this would give rise to pairs or clusters of vacancies but that short range order would exist. A pair of adjacent vacancies forms an empty and unfavorable cage of thirteen sulfur atoms. The presence of an empty cage of eight anions, resulting from a single vacancy, might account for the slight expansion of the lattice as the composition approaches that of the sesquisulfide, Ce_2S_3.

DILUENT DOPING

Diluent doping is an attempt to lower the resistance of thermoelectric materials without changing the number of charge carriers. If the number of charge carriers remains constant large changes in the Seebeck coefficient are not expected. A restriction of this type of mobility doping is that it can only be applied to materials having vacancies as in CeS_x, $1{\cdot}5 \geq x > 1{\cdot}33$ (Th_3P_4 structure).

Earlier workers [5] in the field have shown that just as one can make Ce_3S_4

$$Ce_2S_3 + CeS \rightarrow Ce_3S_4 \tag{1}$$

one can make Ce_2SrS_4

$$Ce_2S_3 + SrS \rightarrow Ce_2SrS_4 \tag{2}$$

where the compound Ce_2SrS_4 has the Th_3P_4 structure. In this compound there are no vacant metal sites and cerium atoms are essentially diluted such that their concentration is $\frac{3}{4}$ the value in Ce_2S_3. There is no change in the formal valence of cerium in this process. Although the ratio Ce^{+2}/Ce^{+3} is unchanged, the carrier concentration, which is equal to the number of formal Ce^{+2} per unit volume, is somewhat diluted as noted above. Therefore,

this method may be termed "diluent doping" in contradistinction to the usual term "doping".

The maximum amount, y_{max}, of diluent dopant which may be added is dependent upon the composition and the doping material. For chalcogenides of divalent metals equation (4) gives the relationship between x and y_{max}

$$CeS_x + y_{max}\,MS \rightarrow CeM_{y_{max}}\,S_{(x+y)_{max}} \tag{3}$$

$$\frac{(x+y)_{max}}{(1+y)_{max}} = 4/3 \tag{4}$$

or

$$y_{max} = 3x - 4$$

where

$$1{\cdot}5 \geq x \geq 1{\cdot}333$$

and is derived on the basis of a filled structure. For monovalent materials equation (6) applies. Of course such things as solubilities and phase changes may be the limiting factors.

$$CeS_x + y_{max}\,Ag_2Se \rightarrow CeAg_{2y_{max}}\,S_xSe_{y_{max}} \tag{5}$$

$$y_{max} = 1/5(3x - 4) \tag{6}$$

where

$$1{\cdot}5 \geq x \geq 1{\cdot}333$$

Doping with a sesquisulfide (e.g., Al_2S_3) would increase the number of trivalent metal ions as well as increase the number of vacant sites. It is also possible that sulfides of some monovalent or divalent metals might be unsuitable for use as a diluent dopant if they changed their formal valence when placed in the host lattice. The added material could no longer be called a diluent dopant because the carrier concentration would have undergone a significant change.

The composition $CeS_{1{\cdot}40}$ can be considered as a case where half a mole of CeS has been homogenized with a mole of Ce_2S_3 leaving a somewhat smaller number of vacancies than in $CeS_{1{\cdot}50}$ (see Table 1, 1 and 4). To this composition, $CeS_{1{\cdot}40}$, either a divalent or monovalent sulfide can be added as a diluent doping agent to fill the vacant cation sites. The maximum amount that can be added is shown in both cases at the bottom of Table 1, entries 5 and 6. The important thing to note is that in the last three cases, numbers 4, 5, and 6, the average cerium charge is unchanged, and as a consequence the electron concentration remains unchanged except for the slight dilution noted earlier.

TABLE 1. EXAMPLES OF DILUENT DOPING

	Average cerium charge	Part Ce^{+3}	Part Ce^{+2}	Part cationic vacancy	Part M^{+2} M+Ce	Part M^{+} M+Ce	Ratio Ce^{+2}/Ce^{+3}
1. $CeS_{1{\cdot}5}$	+3	8/9	0	1/9	0	0	0
2. $CeS_{1{\cdot}333}$	+2–2/3	2/3	1/3	0	0	0	1/2
3. $CeS_{1{\cdot}5}(SrS)_{0{\cdot}5}$	+3	2/3	0	0	1/3	0	0
4. $CeS_{1{\cdot}40}$	+2·80	16/21	4/21	1/21	0	0	1/4
5. $CeS_{1{\cdot}40}(M^{++}S)_{0{\cdot}2}$	+2·80	2/3	1/6	0	1/6	0	1/4
6. $CeS_{1{\cdot}40}(M_2^{+}S)_{0{\cdot}04}$	+2·80	20/27	5/27	0	0	2/27	1/4

In order to see the effect of diluent doping on electron mobility consider the following simple argument. In Ce_3S_4 where the average formal cerium charge is $+2\frac{2}{3}$, approximately the same charge of $-2\frac{2}{3}$ is attracted toward that metallic site from the neighboring sulfur atoms. If then a cerium ion is removed, the geometry of the lattice restrains much of the negative charge to the same locale. A moving electron will see at this vacancy not the charge of $2\frac{2}{3}$ but rather something amounting to almost $-2\frac{2}{3}$ and hence will probably be scattered at the vacancy site. Now if this vacancy is filled with, say, Sr^{++} then much of the potential barrier is smoothed out and the electron mobility is increased.

In addition to any chemical effects, such as increased stability and decreased self-diffusion rates, which might accrue to a filled-lattice compound, the dominant advantage of diluent doping is probably its effect on electron mobility.

TABLE 2. EFFECT OF DILUENT DOPING ON ELECTRICAL PROPERTIES OF $CeS_{1.42}$ AT 50°C

Composition	ρ(ohm-cm) ($\times 10^{-3}$)	$\alpha(\mu V/°C)$
$CeS_{1.42}$	24·5	−34
$CeS_{1.42}(SrS)_{0.09}$	5·1	−36
$CeS_{1.42}(SrS)_{0.18}$	5·7	−60

Table 2 gives an example of the effectiveness of strontium sulfide as a diluent dopant for cerium sulfide ($x = 1{\cdot}42$) at 50°C. The pellets were prepared, pressed, and sintered in argon at approximately 1425°C for 15 min.* Our data to date may be summarized as follows:

1. Most of the resistance decrease observed at room temperature occurs when the amount of dopant added corresponds to about $\frac{1}{3}y_{max}$.
2. Diluent doping is most effective when the number of vacancies is large, that is when x is near to 1·50.
3. At high temperatures the advantages of diluent doping appear to be greatly decreased and may be reversed by increases in thermal conductivity. This is suggested by Fig. 4 where the samples were chosen from those whose relevant properties were known and where an attempt was made to match the Seebeck coefficients.

SOME EXPERIMENTAL PROBLEMS IN HIGH TEMPERATURE MEASUREMENTS

Sintered samples were measured in a dry hydrogen atmosphere at high temperatures (up to 1400°K) in an apparatus constructed of molybdenum (for non-reactive contact with the sample), stainless steel (for thermocouple protection and cylinder walls) and boron nitride (as an electrical insulating material). Early results had the general appearance of Fig. 5 which shows a maximum in Z near 1000°K and a rapid deterioration in electrical properties with higher temperatures. During the course of the measurements the sample was maintained at temperatures in excess of 500° for approximately six hours after the system had been pumped out overnight at slightly elevated temperatures. A high-resistance coating always developed on the exposed portion of the samples. When the heating cycle time was decreased somewhat better high temperature results were noted.

* More complete experimental details will be published at a later date.

Thereafter the time to determine the electrical properties was decreased in order to minimize sample decomposition. Figure 6 demonstrates the advantage of this procedure where the high temperature measurements of $CeS_{1.37}$ were completed in less than an hour. After completion of the measurements, the sample was held at 1400°K for an additional

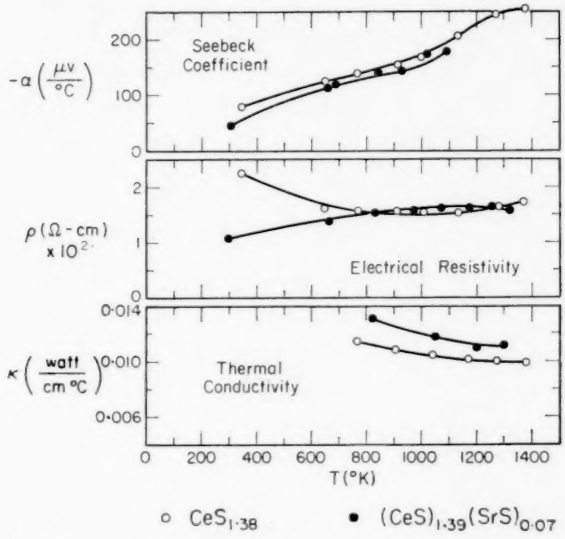

FIG. 4. Comparison of properties of $CeS_{1.38}$ and $CeS_{1.39}(SrS)_{0.07}$.

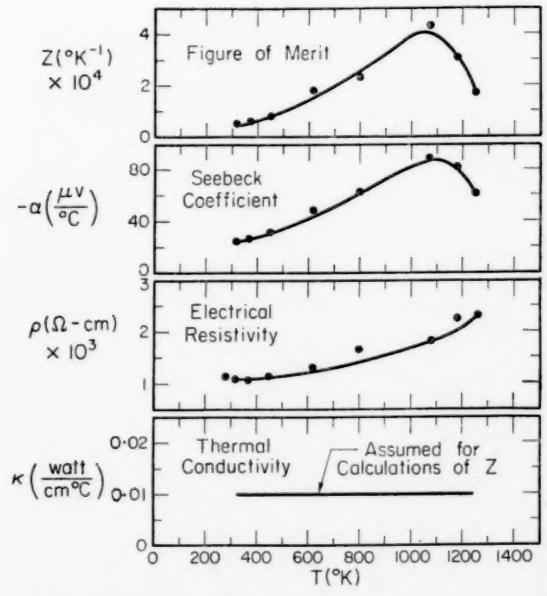

FIG. 5. Electrical properties of $CeS_{1.37}(SrS)_{0.038}$. The sample was held above 500°C for approximately six hours.

two hours. During this time the Seebeck coefficient dropped approximately 10 per cent and the resistivity increased somewhat. Emission spectrographic analysis of the sample after the run showed roughly 1 per cent boron on the surface and a small amount, ca. 0·001 per cent in the interior. This boron probably came from the boron nitride which was used for electrical insulation. It is not certain whether the boron was transported to the sample as volatile B_2O_3 which is present as an impurity and bonding agent or as some other gaseous compound. Nor is it certain whether it is the boron or some other contaminant, e.g., oxygen, which causes the observed electrical deterioration.

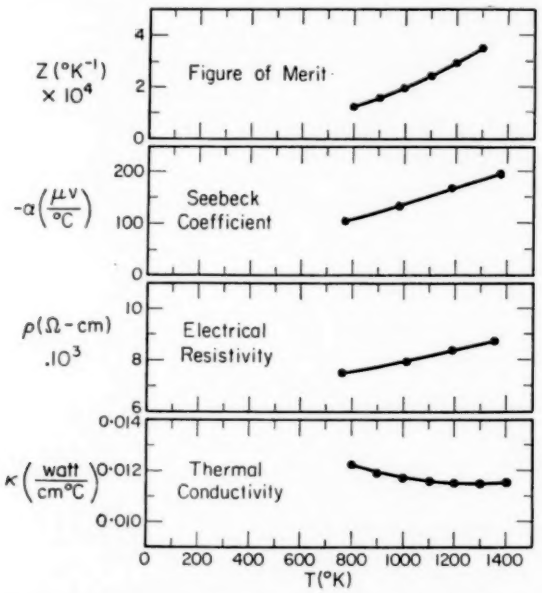

FIG. 6. Thermoelectric properties of $CeS_{1.37}$. The sample remained above 500°C for less than one hour.

CONSIDERATIONS INVOLVING ELECTRICAL CONDUCTION IN CERIUM SULFIDE (THORIUM PHOSPHIDE STRUCTURE)

The mode of electrical conduction in cerium sulfide is not well understood. Several of the possible modes will be discussed utilizing the above structure considerations in corroboration with well-known chemical concepts.

The Hall coefficient in cerium sulfide has been measured by one of the authors and indicates a low electron mobility (ca. 3 cm^2/V sec. for $CeS_{1.37}$ at room temperature). A free-electron picture with long mean free path does not appear applicable.

The cerium–cerium distance in $CeS_{1.40}$ is 4·04 Å. If the metallic single bond radius of 1·646 Å is used for cerium, the bond-order (n) may be estimated from equation (7) according to Pauling [6] to be 0·057. A single bond

$$\Delta R = -0{\cdot}300 \log n \tag{7}$$

would be considered to exist if $n = 1$; if $n < 0{\cdot}05$ one would say that the atoms are non-bonded. A value of $n = 0{\cdot}057$ is, then, just at the borderline and probably does not indicate

significant bonding. If electrical conduction were by means of the metal–metal linkages then a decrease in metal–metal bond distance should give an exponential increase in overlap and a sharp fall in resistivity. However, resistivity measurements of Ce_3S_4 vs. pressure* showed only a 10 per cent linear decrease in resistance at 10,000 atm. Hence it does not seem that metal–metal contacts play an important role in the conduction mechanism.

We shall now consider the possibility of electrical conduction in which the electrons are localized on the anion structure. If Zachariasen's value [2] of $x = 1/12$ is accepted for the sulfur parameter we note from Fig. 3 that an unusually short sulfur–sulfur distance occurs, i.e., 3·22 Å, as compared with 3·68 Å for anionic or van der Waal's radii. On the other hand a calculation of the bond order, equation (7), using a single-bond radius of 1·04 Å for sulfur, indicates that the atoms are non-bonded. Hence the suggestion follows that considerable repulsive forces are operating in this close contact. An examination of the structure shows that these close sulfur atoms form two independent but interwoven three-dimensional arrays. Any pressure tending to compress the structure would work principally through these two non-connected sulfur anion arrays and be expended in large measure further compressing an already short distance. On the other hand any increase in the average negative charge localized on the anions would tend to expand the lattice as well as decrease any sulfur–sulfur bonding that did exist. Therefore, if the anion lattice were to accept electrons from a large part of the cations with a formal charge of $+2$ (this would include 1/3 of all the cations in Ce_3S_4), one would predict a sizeable expansion in the cell edge as the composition approached Ce_3S_4. This is in contradiction to the measured contraction of 0·01 Å. This suggests that the conduction electron is not localized on the anionic structure.

Final considerations are concerned with the possible nature of a trapping mechanism, if indeed one exists. The general theories of polaron motion [7] might be expected to apply even though the trapping mechanism we suggest is covalent rather than wholly polar. Whether the motion of the suggested trap would be associated with an energy of activation or a tunnelling process is not subject to discussion on the basis of existing data. A covalent picture suggests that the sulfur parameter as reported by Zachariasen [2] for cerium sesquisulfide ($x \cong 0{\cdot}083 \pm 0{\cdot}015$) is one or two hundredths too large but possibly still within his limit of error.

When $x = 1/12$ (or 0·083) the sulfur atom is centrally located in a twisted trigonal prism of cerium cations. The cerium–sulfur distance, 2·98 Å, is then in excellent agreement with the ionic sum (2·97 Å) for trivalent cerium. However, there are three sulfur atoms near the top of the prism that strongly repel the centrally located sulfur atom. This repulsive force would be greatly diminished if the parameter x was somewhat smaller, say approximately 0·06. The only force opposing this movement would be the lengthening of the Ce–S bond in the long tetrahedron, type *a*. (See Fig. 3.)

In passing, we note that an argument, though weak, can be aligned against a purely ionic picture of cerium sulfide containing Ce^{+2} ions. These cations might be expected to have a radius of about 1·20 Å. Since in Ce_3S_4 they exist in 33 per cent population, a cell edge increase of 0·07 Å might be calculated in contradistinction to the small decrease of 0·01 Å noted. In the Sm_3S_4 system such a cell edge increase is noted in agreement with the magnetic data supporting the existence of Sm^{+2} ions [4].

An estimate of the covalent or metallic valence V of cerium may be calculated according

* From a private discussion with S. W. Kurnick, of General Atomic.

to Pauling [6] by means of equations (8) and (9).

$$V_{(Ce)} = \Sigma n \quad \text{for all Ce–S bonds} \tag{8}$$

$$d(n) = R_1(\text{Ce}) + R_1(\text{S}) + 2\Delta R \tag{9}$$

$$\Delta R = -0{\cdot}300 \log n \tag{7}$$

$$R_1(\text{Ce}) = 1{\cdot}646\ \text{Å} \qquad R_1(\text{S}) = 1{\cdot}04\ \text{Å}$$

where R stands for metallic radius, d for the cerium-sulfur distance and n for the bond order. The valence of cerium is shown as the top curve against x, the sulfur parameter, in Fig. 7. The two lower curves indicate the contributions of the bonds in the long tetrahedron (L.T.) and in the flat tetrahedron (F.T.), respectively, $4n_1$, $4n_2$. The dash lines at $V = 3$

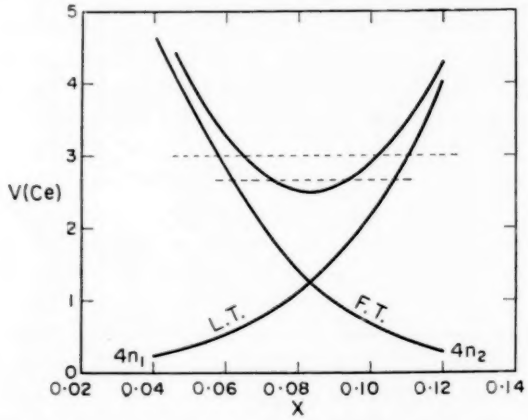

FIG. 7. Metallic valence, V(Ce), of cerium in Ce_3S_4 systems as a function of metalloid parameter, x.

and $V = 2{\cdot}66$ indicate the average formal valence of the metal for Ce_2S_3 and Ce_3S_4, respectively. This model of the structure also suggests that the value of $x = 1/12$ is unfavorable for the sulfur parameter. The right-hand portion of the curve ($x > 1/12$) need not be considered because of the close sulfur–sulfur contacts. We shall give attention to the portion between $x = 0{\cdot}065$ and $0{\cdot}075$. Assume that in a certain locality the average sulfur position was approximately $0{\cdot}075$. The metallic valence of the cerium would then be roughly $2\frac{2}{3}$. By a small shift in the sulfur positions of $0{\cdot}09$ Å (corresponding to $\Delta x \simeq 0{\cdot}01$), the average metallic valence would be increased to 3. That is, an electron could be accepted into a cluster of three cerium atoms. It is further interesting to note that for a single sulfur atom x can be decreased as much as $0{\cdot}01$ before that sulfur atom comes into van der Waal's contact with the unmoved sulfur atoms located in the direction of smaller x. Hence it is not necessary to consider clusters of cerium atoms as a single metal atom may be able to accept an electron by forming stronger bonds with the sulfur atoms in the flat tetrahedron. These atoms would move in such a manner as to make the tetrahedron less flat. A calculation of the ionic character [6] of the Ce–S bond from an electronegativity difference of $1{\cdot}4$ gives an estimate of the charge transfer of $1{\cdot}17$ electrons from the cerium to the sulfur neighbors. Hence more orbitals than are used in the metallic state of cerium are not required in accepting an electron and assuming a higher valence.

An exact calculation of this type is not defensible, of course, but the above approach does suggest that a covalent trapping mechanism may be operative in electronic conduction in cerium sulfide (Th_3P_4 phase).

Such a trapping mechanism will permit the correlated movement of the trap and the charge carrier in a manner similar to that of polaron conduction. The mobility might also be expected to be related to certain vibration modes (e.g., symmetrical vibration of the flat tetrahedrons about the metal site). The use of bond formation as an integral part of the trapping mechanism locates the charge carrier mostly on the metal without contradicting magnetic data [1, 4] (which does not support the existence of Ce^{+2} ions).

In regard to the possible conduction modes in the Th_3P_4 phase of cerium sulfide, we note the following three points:

1. Conduction via the metallic structure alone does not seem to be applicable.
2. Lattice changes as well as magnetic data do not support the viewpoint of the localized charge carrier on either the metal or the metalloid.
3. If the trapping of the charge carrier is an important part of the conduction mode, then the trapping mechanism involves the formation of covalent bonds rather than being wholly polar in its nature.

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SYNTHESIS AND PROPERTIES OF THE SAMARIUM SULFIDES*

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ABSTRACT

THE RARE earth compounds have been extensively investigated for refractory and semiconductor applications, more specifically for thermoelectric power generation. Samarium sulfides were synthesized by direct reaction of the elements in sealed quartz chambers at temperatures in the range 600°–800°C. Thermoelectric and X-ray structure data were obtained on polycrystalline compacts or powders. The analysis of the Sm–S system established four definite compounds, SmS, Sm_3S_4, Sm_2S_3 and SmS_2, all cubic, and a series of solid solutions from Sm_3S_4 to Sm_2S_3. This binary mixture is analogous to that reported for Ce–S and probably applies to most of the rare earth–sulfur systems. The electrical characteristics change from insulating to semiconducting as the samarium/sulfur ratio increases. One mixed valence compound, $Sm^{II}Sm^{III}_2S_4$, is suggested by the magnetic susceptibility data and the conditions for electroneutrality in the crystalline structure. All compounds possess melting points in excess of 1500°C. Semiconducting compounds have thermal conductivities of 10^{-2} W/°C-cm and good thermoelectric characteristics up to 1000°C. Precautionary measures to prevent oxidation must be applied when utilizing the material at high temperatures.

* The entire text of this paper appeared in *Ceramic Age*, September (1961).

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THERMOELECTRIC PROPERTIES OF RARE EARTH CHALCOGENIDES

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Summary—Sesqui-oxides, sulphides, selenides and tellurides of several rare earths have been prepared and measurement made of their Seebeck coefficients and electrical resistivities over the temperature range 30–1000°C.

Data have also been collated from the literature to show that for a given rare earth, Seebeck coefficients decrease in the general order selenide > sulphide > telluride > oxide. For a specific chalcogenide anion, resistivities decrease with increasing atomic number of the rare earth as far as gadolinium and then increase.

The factors, σ^2/ρ, generally show maxima at gadolinium compounds and this is thought to substantiate the theory that transport mechanisms in these materials involve $4f$ orbital electrons.

INTRODUCTION

THE INCREASING availability of rare earth compounds of high degrees of purity has led to wider investigations of their properties. Particularly has this been so in electronics areas and more specifically in the field of energy conversion where some of the unique properties attendant upon $4f$ electron transitions have been applied, e.g. in maser and laser materials. Recent work has also shown that rare earth chalcogenides, when appropriately treated, offer some promise as thermoelectric materials. The known wide energy gaps for such compounds generally preclude their effective use at anything other than high temperatures but, in such areas, conversion of thermal energy to e.m.f. appears remarkably efficient. Because of this, and in order to provide a wide basis for continuing investigations in these laboratories, a survey has been made of the thermoelectric properties of many of the rare earth sesqui-chalcogenides. This has been supplemented by data from other laboratories as noted below.

Earlier work on the gadolinium–selenium system [1, 2] determined that optimum thermoelectric parameters did not stem from the simple sesqui-selenide, but from a metastable system resulting from interaction of this with the mono-selenide. Further papers, submitted for publication elsewhere, present a theoretical rationalisation of the phenomena observed. It has been necessary at this point, however, to retrace our steps and examine more cogently the properties of the pure chalcogenides in order that we may more completely appreciate the transport mechanisms involved in these materials. This paper therefore presents the results of a preliminary survey of the properties of the pure sesqui-chalcogenides of several rare earths.

EXPERIMENTAL

The rare earth oxides examined were obtained from standard sources and were all of 99·9+ per cent purity.

The sulphides, selenides and tellurides were all prepared by direct reaction between the rare earth metal and the chalcogenide element. The technique employed, involving dual temperature heating, has been described previously [1] and is essentially a standard ap-

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† Electronic Materials Corporation, Santa Monica, California.

proach. At this point it must be emphasized however that it has not been found possible to prepare the pure chalcogenides by reaction of the rare earth oxide with e.g. H_2Se, H_2S, etc. Such a procedure invariably leaves at least traces of oxygen in the final product and, in some instances it has not been found possible to carry the reaction to the point at which oxygen contents drop below 1–2 per cent. This may account for varying results reported by other workers [3] on the physical and chemical properties of the sesqui-sulphides, selenides and tellurides.

After such direct reaction, the products were obtained in powder form which was consolidated by induction melting, in an argon atmosphere. By controlled cooling the melt could be obtained in solid form without the occurrence of undue stress cracking and specimens could be selected for measurement of thermoelectric parameters.

Rare earth oxides cannot be thus melted into coherent specimens and recourse therefore was made to the preparation of samples by either hot pressing techniques (temperatures ~1200–1600°C and pressures ~ 1000–3000 p.s.i. were used), or standard ceramic techniques —i.e. pressing, sintering.

Specimens finally examined were approximately 1 cm × 50 mm × 25 mm in dimension. Resistivities over the temperature range 30°C to 1000°C were measured in argon in both vacuum and at normal atmospheric pressure by the four-point probe technique [4] and Seebeck coefficients by the conventional technique previously described [1]. At this stage no data are available on thermal conductivity values other than those already extant.

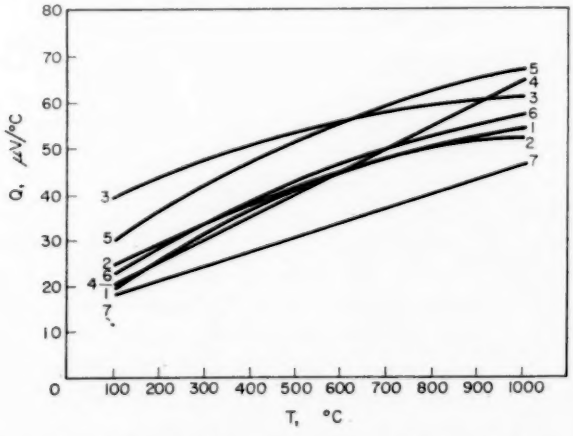

FIG. 1. Seebeck coefficients of rare-earth oxides: 1. Y_2O_3; 2. La_2O_3; 3. CeO_2; 4. Sm_2O_3; 5. Gd_2O_3; 6. Er_2O_3; 7. Yb_2O_3

DATA OBTAINED

Oxides. Seebeck coefficients obtained for the rare earth oxides are shown in Fig. 1. Data points have been averaged with a mean deviation of ±5 per cent. The linearity of e.m.f./temperature curves for samarium and ytterbium oxides is interesting in comparison with the curves of the other oxides and it is felt that this may bear some relation to the potential bivalency of these two rare earth elements. No data have been obtained, or apparently are thus far not available, for europium, praseodymium or terbium oxides.

Resistivity values (Fig. 2) clearly fall into two, and possibly three, classes. Oxides of the potentially bivalent elements again show somewhat anomalous values and these tend to increase with temperature. The ρ/T slope for cerium oxide, whilst generally decreasing with temperature nevertheless might be considered out of conformity with the general range of rare earth oxide resistivities; the same however might also be said for gadolinium oxide since the slope is hardly parallel to that of the other oxides even when deviations of ± 10 per cent are allowed for.

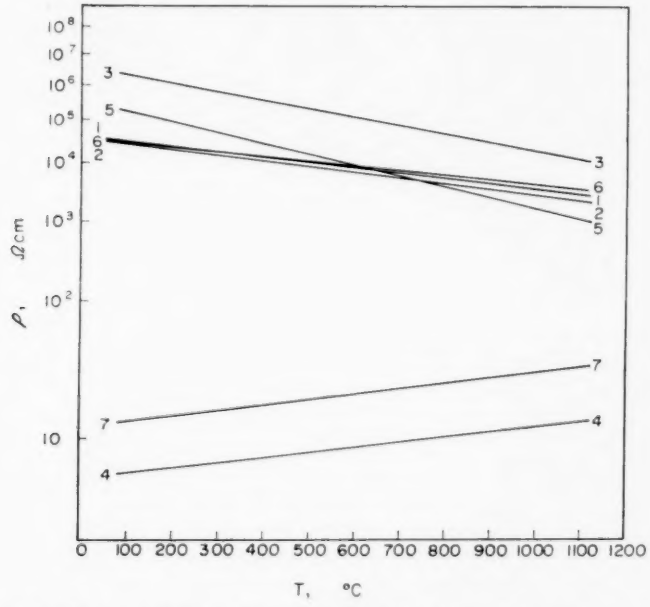

FIG. 2. Electrical resistivities of rare-earth oxides: 1. Y_2O_3; 2. La_2O_3; 3. CeO_2; 4. Sm_2O_3; 5. Gd_2O_3; 6. Er_2O_3; 7. Yb_2O_3.

Sulphides. Figure 3 shows again that anomalous thermoelectric values appear to obtain where the rare earth moiety is capable of bivalence; otherwise Seebeck coefficients clearly increase—at least as far as gadolinium—with increase in atomic number of the rare earth. Our values for cerium and samarium sulphides are in good agreement with those of Carter and Houston [5], but, for cerium sulphide, lower than those reported by Kurnick *et al.* [6]. It is unclear however whether the materials examined by these workers were purely stoichiometric. As has been indicated above, and in earlier work, even mild variations in composition or preparative techniques can grossly alter thermoelectric parameters.

The anomalous resistivity of samarium sulphide is clearly shown in Fig. 4. Sulphides of the other rare earths show decreasing resistivities with increase in temperature but we have been unable to confirm the decreasing values presented by Carter and Houston (*loc. cit.*) for the samarium compound. It must be emphasized however that high temperature measurement of resistivity is as yet insufficiently precise and standardized to warrant the drawing of specific conclusions. It might be possible that samarium sulphide decomposes with increase in temperature yielding a lower valence compound, but that this can be obscured if the original material be not purely stoichiometric.

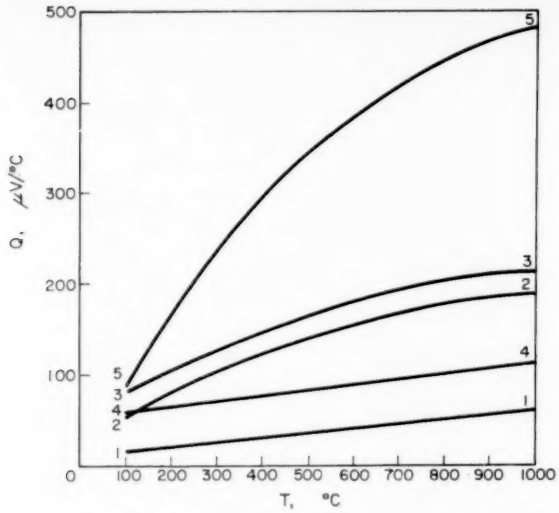

FIG. 3. Seebeck coefficients for rare-earth sulphides: 1. Y_2S_3; 2. La_2S_3; 3. CeS_2; 4. Sm_2S_3; 5. Gd_2S_3.

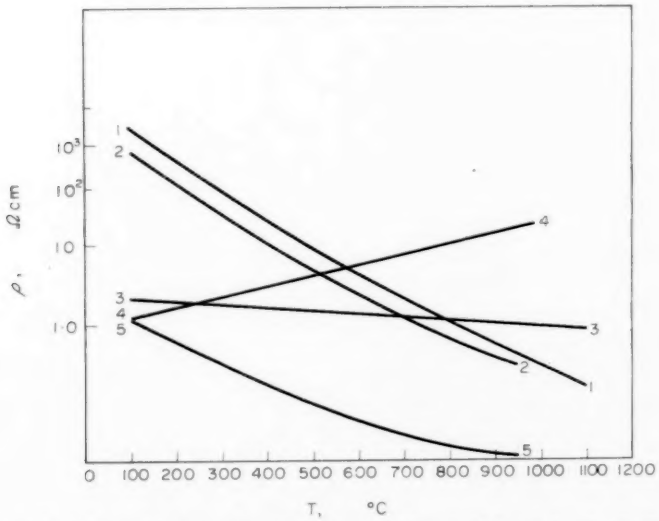

FIG. 4. Electrical resistivities of rare-earth sulphides: 1. Y_2S_3; 2. La_2S_3; 3. CeS_2; 4. Sm_2S_3; 5. Gd_2S_3.

Selenides. Seebeck coefficients for those compounds for which data are available display behavior similar to that seen in the sulphides (Fig. 5). Again the gadolinium compound presents the highest thermal e.m.f. values of those examined. Ytterbium selenide shows none of the anomalies previously seen and thought ascribable to possible valence variations.

Resistivities for this series (Fig. 6) show that the sigmoid type curve, earlier noted for gadolinium selenide, is manifested also by the lanthanum, erbium and ytterbium compounds.

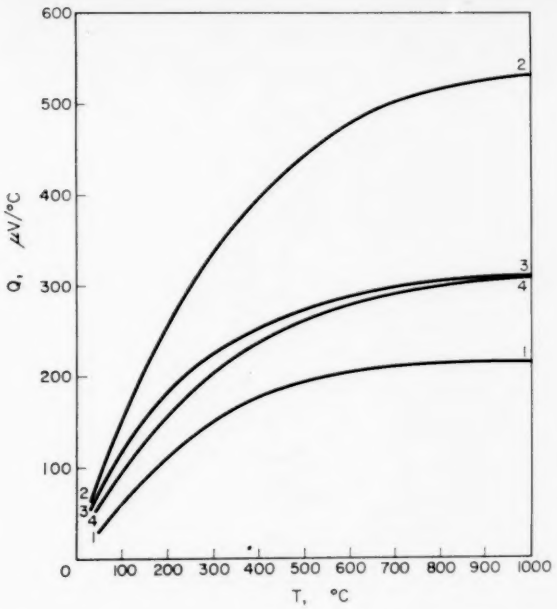

FIG. 5. Seebeck coefficients of rare-earth selenides: 1. La_2Se_3; 2. Gd_2Se_3; 3. Er_2Se_3; 4. Yb_2Se_3.

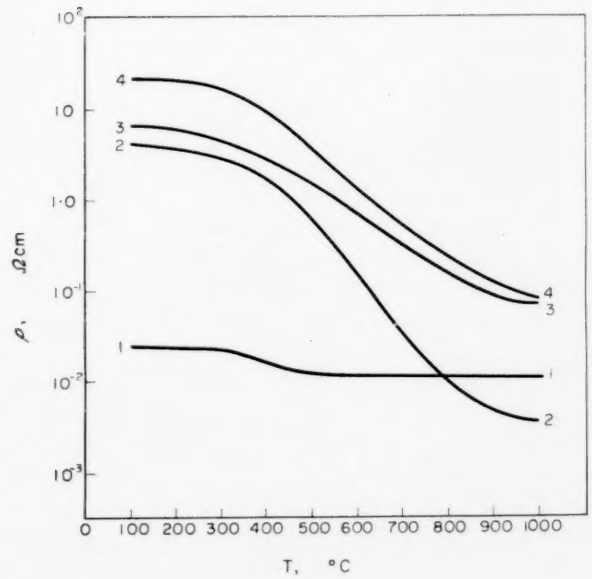

FIG. 6. Electrical resistivities of rare-earth selenides: 1. La_2Se_3; 2. Gd_2Se_3; 3. Er_2Se_3; 4. Yb_2Se_3.

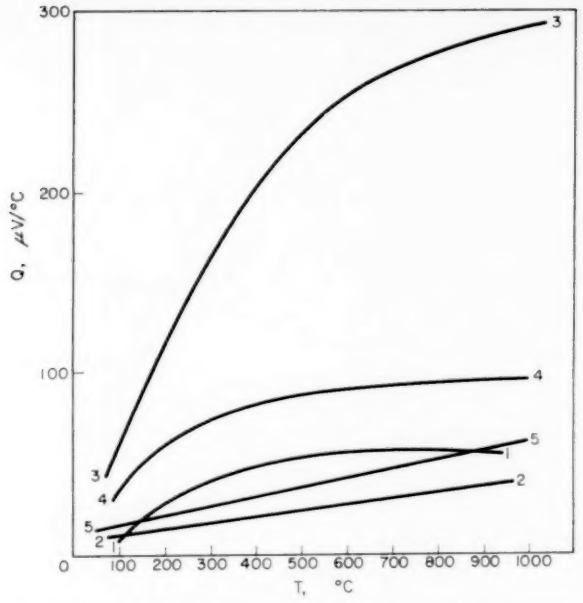

FIG. 7. Seebeck coefficients for rare-earth tellurides: 1. La_2Te_3; 2. Sm_2Te_3; 3. Gd_2Te_3; 4. Er_2Te_3; 5. Yb_2Te_3.

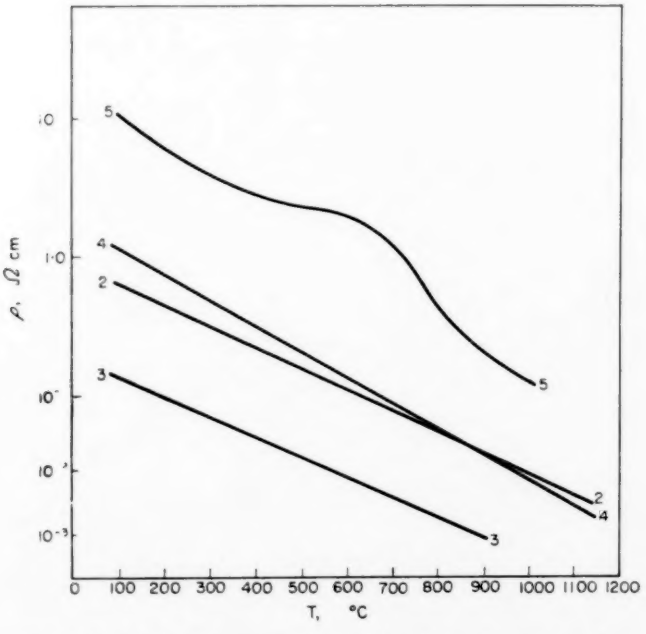

FIG. 8. Resistivities of rare-earth tellurides: 2. Sm_2Te_3; 3. Gd_2Te_3. 4. Er_2Te_3; 5. Yb_2Te_3.

Miller and Himes [7] report a room temperature resistivity for La_2Se_3 of 0·024 Ω-cm at 30°C; our present value is somewhat higher than this at 100°C and, whilst the sigmoid nature of the ρ/T curve can still be seen in the figure, it is less marked than in the other selenides. By direct comparison however, resistivities for this selenide are certainly lower than those of the other selenides prepared and examined.

Tellurides. Miller and Himes (*loc. cit.*) have reported thermoelectric data for several rare earth tellurides. Some agreement is found between these earlier data and results from present work. The different values previously reported for *p* and *n* type Gd_2Te_3 re-emphasize the point earlier made that minor preparation variables can grossly affect the electrical data obtained.

Seebeck values now found are shown in Fig. 7 and again chalcogenides of the potentially bivalent rare earths, ytterbium and samarium present anomalously straight-line values as compared with the arched curves of the other chalcogenides. As indicated above, reasonable agreement is found between the earlier data of Miller and Himes and that now presented for the lanthanum and gadolinium compounds.

Resistivities found for the tellurides are almost uniformly low (Fig. 8) and again in some agreement with earlier data. Somewhat surprisingly samarium and ytterbium tellurides do not display much similarity in ρ/T curves and only that of the latter telluride exhibits the sigmoid type curve seen in the selenide compounds.

DISCUSSION AND SUMMARY

Seebeck-coefficient data suggest that in rare earth sesqui-chalcogenide series, thermally generated e.m.f.'s increase through the rare earth series as far as gadolinium and then decrease. For a given rare earth element also, Seebeck coefficient values tend to drop in the order selenides > sulphides > tellurides > oxides. Where deviations from these sequences are noted it is possible that they may represent valence variation in the rare earth moiety.

For a given chalcogenide anion, resistivities appear to decrease with increasing atomic number of the rare earth as far as gadolinium and thereafter to increase. For a given rare earth, resistivities of sesqui-chalcogenides appear to decrease with increasing atomic weight of the chalcogenide.

More specific correlation of thermoelectric power is given in Fig. 9. Plots of α^2/ρ vs. rare earth show quite distinctly that thermoelectric values at 800°C peak at gadolinium for all systems except that of the oxides. Further work on the oxide systems is intended since most recent studies have shown that such materials can attain quite low resistivities when suitably treated.

If one considers only the chalcogenides of a given rare earth element, variations of ρ and α values are in conformity with accepted extrinsic semiconductor theory, i.e. increased charge mobility with increasing atomic weight, etc. Looking at the data from the rare earth metal aspect however, we must account for maxima and minima obtaining at gadolinium. Similar observations of sequential maxima and minima are seen in other properties of a series of rare earth compounds [8]. In general these have been attributed to ionic radii 4*f*-electron density relationships and it may well be that in the chalcogenides a similar effect is seen. If so some support can then be elicited for the theory that, in the rare earth series the low lying 4*f* electrons do play a significant part in transport mechanisms [9]. Apparently anomalous variations in electrical properties of the chalcogenides of samarium

and ytterbium—both having marked tendency towards bivalency—might be considered further supporting evidence for this theory since bivalence—or quadrivalence in the case of cerium, praseodymium or terbium—is known to affect the $4f$ orbital electron population.

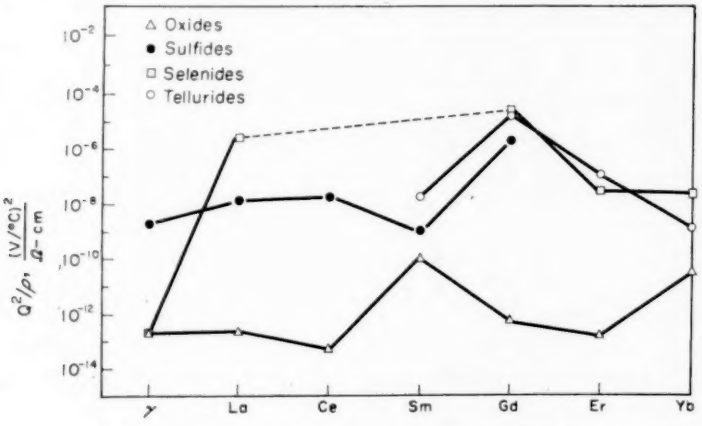

FIG. 9. S^2/ρ for rare-earth chalcogenides at 800°C.

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Advanced Energy Conversion. Vol. 1, p. 187. Pergamon Press, 1961. Printed in Great Britain

SEMICONDUCTING PROPERTIES OF AMORPHOUS MATERIALS*

H. L. UPHOFF and J. H. HEALY†

ABSTRACT‡

TEN COMPOSITIONS in the systems As : Se : Te and As : S : Te were synthesized, and nine of the ten were amorphous in structure.

The resistivities of the materials in both systems were determined at temperatures up to 373°K. The resitivities varied exponentially with the inverse of the absolute temperature. At room temperature (298°K), the resistivity values ranged from $4{\cdot}7 \times 10^4\ \Omega$ cm to $2{\cdot}5 \times 10^{13}\ \Omega$ cm. At any temperature, the material resistivity values decreased with increase in tellurium content.

The Seebeck coefficient values of the amorphous materials in the system As : Se : Te were determined over the same temperature range as the resistivity values. All of the amorphous materials were *p*-type and all possessed a negative temperature coefficient of the Seebeck coefficient. In most cases, the Seebeck coefficient temperature dependence can be represented by a straight line. At room temperature (298°K), the Seebeck coefficient values range from 1070 μV/°C to 1625 μV/°C.

The thermal conductivities of the materials in the system As : Se : Te were determined, the values for the amorphous materials in this system range from 3·3 — 4·1 mW/cm°C, and they show very little variation as a function of material composition.

* This work was sponsored by the Office of Naval Research under contract NONR 2965(00) and is continuing under Amendment 1.

† A. O. Smith Corporation, Milwaukee, Wisconsin.

‡ The full text of this paper appeared in *J. Appl. Phys.* **32**, 950 (1961).

Advanced Energy Conversion. Vol. 1, p. 189. Pergamon Press, 1961. Printed in Great Britain

THERMOELECTRIC POWER AND ELECTRICAL CONDUCTIVITY OF MOLTEN BINARY THALLIUM ALLOYS*

DONALD F. STONEBURNER†

ABSTRACT

AN INVESTIGATION was undertaken to determine the thermoelectric properties of a series of binary liquid compositions having one element in common. Thallium was chosen as the common element, and liquid alloys of thallium with arsenic, antimony, bismuth, sulfur, selenium and tellurium were studied. The thermoelectric power and electrical conductivity were measured as a function of temperature for each composition investigated, and the temperature dependence of both were noted.

The results of this investigation indicated metallic behavior for the alloys of thallium with arsenic, antimony, and bismuth, while the sulfides, selenides, and tellurides exhibited semiconduction. The results are compared with the properties of the same composition in the solid state, where such information is available in the literature. The work of this investigation confirms the observation that long-range order is not a necessary requirement for semi-conduction. Changes in thermoelectric properties of semiconductors on fusion have been related to the change in bonding on fusion.

* The complete version of this paper has been submitted for publication in *Trans. AIME.*

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THERMOELECTRICITY ABSTRACTS

Compiled by
MILDRED BENTON,
U.S. Naval Research Laboratory

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ABSTRACTS

Compiled by MILDRED BENTON, U.S. Naval Research Laboratory

INTRODUCTION

IN SUPPORT of co-ordinated scientific effort of the Armed Forces thermoelectric programme, the Material Development Branch, Bureau of Ships, requested the Library of the U.S. Naval Research Laboratory to service as a Centre for the collection, maintenance and publication of references to the literature on thermoelectric research, development and application.

Sources utilized in the preparation of this bibliography include current periodicals and research reports received in the Library of the U.S. Naval Research Laboratory and the following index and abstract journals:—

Abstracts Journal, Metallurgy (USSR)
Applied Mechanics Reviews
Applied Science and Technology
ASM Review of Metal Literature
Battelle Technical Review
Bell Telephone Laboratories. Technical Information Libraries. Index to Current Technical Literature
Ceramic Abstracts
Chemical Abstracts
Dissertation Abstracts
East European Accessions Index (Library of Congress)
Engineering Index
Institute of Radio Engineers. Proceedings
Instrument Abstracts
Metallurgical Abstracts
Monthly Index of Russian Accessions (Library of Congress)
Nuclear Science Abstracts
Readers Guide to Periodical Literature
Science Abstracts (Section A. Physics Abstracts; Section B. Electrical Engineering Abstracts)
Semiconductor Abstracts
Technical Abstract Bulletin (ASTIA)
Technical Translations
U.S. Government Research Reports (OTS).

Within each subject category the arrangement for periodical entries is alphabetical—by author, or by title if author is lacking; and for research reports—by issuing agency. Each entry is numbered in preparation for an anticipated index. Abbreviations for journal titles are based on those used by the U.S. Naval Research Laboratory Library. A list of these abbreviations, together with the journals which they represent, appears on the pages following this introduction.

The majority of the publications referred to should be available for consultation or borrowing at the larger public or research libraries. Research reports can usually be obtained from the Armed Services Technical Information Agency (ASTIA), Arlington Hall Station, Arlington 12, Va., through established borrowing procedures and from the Office of Technical Services (OTS), Washington 25, D.C., by purchase. AD numbers (for ASTIA material) and PB numbers for (OTS material) are included, when known, in order to facilitate use of ASTIA or OTS services.

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Suggestions concerning this bibliography are encouraged by the compiler, Miss Mildred Benton, Consultant in Research Information, U.S. Naval Research Laboratory, Code 2023, Washington 25, D.C.

ABBREVIATIONS USED IN CITATIONS TO PERIODICALS

The following is a list of abbreviations used in citing references to periodicals, followed by the complete title of the periodical.

Acad. Sci. Paris. Compt. Rend.	Académie des Sciences, Paris. Comptes Rendus Hébdomadaires des Séances.
Acta Met.	Acta Metallurgica
Acta Phys. Polon.	Acta Physica Polonica
Air Univ. Quart. Rev.	Air University Quarterly Review.
Akad. Nauk. SSSR. Dok.	Akademiya Nauk. SSSR. Doklady
Akad. Nauk. SSSR. Inst. Obshchei i Neorg. Khim. Izvest. Sektora Platiny i Drug Blagorod. Metal.	Akademiya Nauk, SSSR. Institut Obshchei i Neorganiheskoi Khimii. Izvestiya Sektora Platiny i Drugikh Blagorodnykh Metallov.
Akad. Nauk. SSSR. Izvest.	Akademiya Nauk, SSSR. Izvestiya
Akad. Nauk. SSSR. Ser. Fiz. Izvest.	Akademiya Nauk, SSSR. Seriya Fizicheskaya Izvestiya
Akad. Nauk. SSSR. Ural. Filial. Inst. Fiz. Metall. Trudy.	Akademiya Nauk, SSSR. Ural'skii Filial. Instituta Fiziki Metallov. Trudy.
Akad. Nauk. SSSR. Vest.	Akademiya Nauk, SSSR. Vestnik
Algiers Univ. Pub. Sci. Ser. B.	Algiers Universite. Publications Scientifiques, Serie B.
Am. Inst. Mining Engrs. Met. Soc. Trans.	American Institute of Mining Engineers. Metallurgical Society. Transactions.
Am. J. Sci.	American Journal of Science.
Am. Phys. Soc. Bull.	American Physical Society. Bulletin.
Am. Soc. Mech. Engrs. Trans.	American Society of Mechanical Engineers. Transactions.
Ann. Physik.	Annalen der Physik
Ann. Radioélec.	Annales de Radioélectricité
Appl. & Indus.	Applications and Industry
Arch. Tech. Messen.	Archiv. für Technisches Messen
Arch. Eisenhüttenw.	Archiv für das Eisenhuttenwesen
Armed Forces Chem. J.	Armed Forces Chemical Journal
ARS J.	ARS Journal
Atlantic Mon.	Atlantic Monthly.
Aviat. Wk.	Aviation Week
Brit. Comm. & Electron.	British Communications and Electronics
Brit. J. Appl. Phys.	British Journal of Applied Physics
Bus. Wk.	Business Week
Can. J. Phys.	Canadian Journal of Physics
Ceram. Indus.	Ceramic Industry
Chem. & Eng. News	Chemical and Engineering News
Collection Czechoslov. Chem. Comm.	Collection of Czechoslovak Chemical Communications
Comm. & Electron.	Communication and Electronics
Dig. Soviet Tech.	Digest of Soviet Technology
Dissertation Abs.	Dissertation Abstracts
Elec. Eng.	Electrical Engineering
Elec. Mfg.	Electrical Manufacturing
Elec. Rev.	Electrical Review
Elec. World	Electrical World
Electrochem. Soc. J.	Electrochemical Society. Journal
Electrochem. Soc. Trans.	Electrochemical Society. Transactions
Electron.	Electronics
Electron. Tech.	Electronic Technology
Electrotech. Lab. Bull. (Japan).	Electrotechnical Laboratory. Bulletin. (Japan).
Elektrotech. Obzor.	Elektrotechniky Obzor
Eng.	Engineering
Eng. Mat. & Design	Engineering Materials and Design
ETZ	Elektrotechnische Zeitschrift

Faraday Soc. Trans.	Faraday Society. Transactions
Fiz. Met. i Metalloved.	Fizika Metallov i Metallovedeniya
Fiz. Tverdogo Tela.	Fizika Tverdogo Tela
Frank. Inst. J.	Franklin Institute. Journal.
Helv. Phys. Acta.	Helvetica Physica Acta
Hiroshima Univ. Fac. Eng. Bull.	Hiroshima University. Faculty of Engineering. Bulletin
Iasi Inst. Polit. Bul.	Iasi Institutal Politechnic. Buletinul
Indus. Eng. Chem.	Industrial and Engineering Chemistry
Inst. Elec. Engrs. Proc.	Institution of Electrical Engineers. Proceedings
Inst. Intern. Froid. Bull.	Institut International du Froid. Bulletin.
Inst. Met. im A. A. Baikova. Trudy	Instituta Metallurgii imeni A. A. Baikova. Trudy
Inst. Radio Engrs. Proc.	Institute of Radio Engineers. Proceedings
Inst. Radio Engrs. Trans. CP.	Institute of Radio Engineers. Transactions, Professional Group on Component Parts
Inst. Radio Engrs. Trans. ED.	Institute of Radio Engineers. Transactions, Professional Group on Electron Devices
Instr. & Contr. Sys.	Instruments and Control Systems
Instr. Soc. Am. J.	Instrument Society of America. Journal
Iowa Acad. Sci. Proc.	Iowa Academy of Science. Proceedings
Iron & Steel Inst. J.	Iron and Steel Institute. Journal
Izvest. Vysshikh Ucheb. Zaved. Fiz.	Izvestiia Vysshikh Uchebnykh Zavedenii Fizika
J. Appl. Phys.	Journal of Applied Physics
J. Chem. Phys.	Journal of Chemical Physics
J. Chim. Phys.	Journal de Chimie Physique
J. Electron & Contr..	Journal of Electronics and Control
J. Less Common Metals	Journal of Less Common Metals
J. Nuclear Mat.	Journal of Nuclear Materials
J. Phys. Chem.	Journal of Physical Chemistry
J. Res.	Journal of Research (NBS)
J. Sci. Instr.	Journal of Scientific Instruments
Kholod. Tekh.	Kholodil'naya Tekhnika
Kyushu Univ. Fac. Sci. Mem.	Kyushu University. Faculty of Science. Memoirs
Leeds Phil. & Lit. Soc. Proc.	Leeds Philosophical and Literary Society. Proceedings
Mach. Design.	Machine Design
Meas. Tech. (USSR.)	Measurement Techniques (USSR.)
Met. Rev.	Metallurgical Reviews
Moskov. Univ. Ser. Mat. Mekhan. Astron. Fiz. i Khim. Vestnik.	Moskovskogo Universiteta. Seriya Matematiki, Mekhanki, Astronomii, Fiziki i Khimii. Vestnik
Nachrtech. Z.	Nachrichtentechnische Zeitschrift
Naturw.	Naturwissenschaften
Nauch. Dok. Vys. Shkoly. Met.	Nauchnye Doklady Vysshei Shkoly-Metallurgiya
Ned. Akad. Wetens. Proc.	Koninklijke Nederlandse Akademie Van Wetenschappen
Nuclear Sci. Abs.	Nuclear Science Abstracts
Nuclear Sci. & Eng.	Nuclear Science and Engineering
Onde Elec.	Onde Electrique
Phil. Mag.	Philosophical Magazine
Philips Res. Repts.	Philips Research Reports
Phys. Metals & Metallog. (USSR.)	Physics of Metals and Metallography (USSR)
Phys. Rev.	Physical Review
Phys. Rev. Ltr.	Physical Review Letters
Phys. & Chem. Solids.	Physics and Chemistry of Solids
Phys. Soc. Japan, J.	Physical Society of Japan. Journal
Phys. Soc. Proc.	Physical Society (London). Proceedings
Poluprovodniki v Nauke i Tekh.	Poluprovodniki v Nauke i Tekhnike

Praxis Physik/Chem. Phot.	Praxis der Physik/Chemie Photographie
Pribory i Tekh. Eksp.	Pribory i Tekhnika Eksperimenta
Prod. Eng.	Product Engineering
Radio Eng. & Electron. (USSR.)	Radio Engineering and Electronics (USSR.)
Res.	Research
Rev. Gen. Elec.	Revue Générale d'Electricité
Rev. Mod. Phys.	Reviews of Modern Physics
Roczniki Chem.	Roczniki Chemii
Roy. Soc. Edinburgh. Trans.	Royal Society of Edinburgh. Transactions
Roy. Soc. London. Proc.	Royal Society of London. Proceedings
Sci. Am.	Scientific American
Sci. News Ltr.	Science News Letter
Soc. Automotive Engrs. J.	Society of Automotive Engineers. Journal
Soviet Phys. JETP.	Soviet Physics JETP
Soviet Phys. Solid State	Soviet Physics Solid State
Soviet Phys. Tech. Phys.	Soviet Physics Technical Physics
Space/Aero	Space/Aeronautics
Stanford Res. Inst. J.	Stanford Research Institute. Journal
Tohoku Univ. Res. Inst. Sci. Repts.	Tohoku University. Research Institute. Science Reports
Ukrain. Fiz. Zhurn.	Ukrainskii Fizichnii Zhurnal
U.S. Nav. Res. Lab. Rept. NRL Prog.	U.S. Naval Research Laboratory. Report of NRL Progress.
Westinghouse Engr.	Westinghouse Engineer
Z. Elektrochem.	Zeitschrift für Elktrochemie
Z. Metallk.	Zeitschrift für Matallkunde
Z. Naturforsch.	Zeitschrift für Naturforschung
Z. Physik.	Zeitschrift für Physik
Z. Physik. Chem.	Zeitschrift für Physikalische Chemie
Zhurn. Eksp. i Teor. Fiz.	Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki
Zhurn. Neorg. Khim.	Zhurnal Neorganicheskoi Khimii
Zhurn. Priklad. Khim.	Zhurnal Prikladnoi Khimii
Zhurn. Tekh. Fiz.	Zhurnal Tekhnicheskoi Fiziki

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In German.

Said to be the first important article on Peltier cooling, it includes calculations on the efficiency of Peltier refrigeration. The writer states that with copper–iron thermocouples not even a 2°C temperature difference could be obtained.

Translation available from Special Libraries Assn. Translation Center, 86 E. Randolph, Chic., 1, Ill.

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Entire item quoted.

5. Bate, J. A. **Electric and metallic properties of metals and alloy.** *Australasian Engr.* p. 79–89, Jan. 1952.

This paper is a review of the metallurgical aspects of electrical conductivity, thermoelectricity and ferromagnetism. Thermoelectric effects and factors affecting thermoelectric properties are discussed.

6. Battelle Memorial Institute, Columbus, Ohio. **Thermoelectric power generation and related phenomena.** 7 January–7 March 1959, 5 p., Apr. 15, 1959. (Bimon. Rept. 2) (Contract Nobs-77034).

Includes table giving thermoelectric properties of some n– and p–type Bi_2Te_3 alloys.

7. Battelle Memorial Institute, Columbus, Ohio. **Thermoelectric power generation and related phenomena,** by T. S. Shilladay. 10 p., June 5, 1959. (Bimon. Prog. Rept. 3) (Contract Nobs-77034).

Reports work on Bi_2Te_3 alloys carried out prior to an alteration in scope of the contract. Plots of resistivity (p), thermal conductivity (k), thermoelectric power (a), and the figure of merit (z) as a function of the absolute temperatures are shown for Bi_2Te_3–Bi_2Se_3 alloys.

8. Battelle Memorial Institute, Columbus, Ohio. **Thermoelectric power generation and related phenomena.** 11 p., Aug. 24, 1959. (Bimon. Rept. 4) (Contract Nobs–77034).

Report on materials development (preparation of III–V alloys, physical properties (AlAs), apparatus for measurement of thermal and electrical properties at high temperature), by J. F. Miller, J. I. Genco, *et al,* Report on fundamental properties of thermoelectric materials, by J. J. Duga and A. C. Beer; Thermoconductivity measurements, by P. W. Davis and T. S. Shilladay.

9. Becquerel, H. **Historical note on thermal batteries.** *Elec. World,* **15**: 299, 1890.

Several early experiments in thermoelectricity are discussed. A. C. Becquerel obtained electric currents by plunging a hot carbon rod into molten potassium nitrate contained in a platinum vessel. Another thermocouple, comprising two different metals, immersed in a melted silicate, is described.

10. Beer, A. C. **Semiconducting compounds—a challenge in applied and basic research.** *Electrochem. Soc. J.* **105**: 743–751, Dec. 1958.

A brief outline is given for selecting thermoelectric materials. Some materials are considered—bismuth telluride, indium antimonide. Very little work has so far been done on thermoelectric materials which might be operable at higher temperatures above 600°C.

11. Bishop, T. **New use for Bi and Te.** *Metal Prog.* **67**: 110, June 1955.

A recent demonstration before the Royal Society in London showed a unit employing bismuth and a bismuth tellurium compound which could freeze miniature ice cubes in a small metal tray. Research is to continue and further developments are expected. One possibility is that sources of low-grade waste heat might be used with thermojunction generators to provide the low-voltage high-current supply required to operate the cooling junctions. The same factors which control efficient thermoelectric cooling apply also to efficient thermoelectric generators. The successful development of these to make use of waste heat or solar energy might well provide useful sources of electric power for a variety of applications.

12. Blanke, B. C. **Nuclear thermoelectric conversion.** In Army Signal Research and Development Laboratory, Power Sources Division. Proceedings, 12th Annual Battery Research and Development Conference, p. 110–111, illus., Fort Monmouth, N.J., 1958.

Mentions factors which will determine future trends; also, limitations, two of which are being overcome, i.e., cost of radioisotopes and inefficiency of thermoelectric elements. The third difficulty is inherent in the system and this is the associated gamma radiation with the heat source.

13. BRADLEY, F. N. **Thermoelectricity.** *Ceram. Age* **73**: 52–53, Apr. 1959.

Uses and applications of thermoelectric devices and their importance to the ceramic industry.

14. BRENNAN, W. D. **Experiment in thermoelectricity.** *Am. J. Phys.* **27**: 427, Sept. 1959.

A note attempting to explain the physical reasoning behind a statement by NOON and O'BRIEN (*Am. J. Phys.* **26**: 373, 1958) in their discussion of the operation of a thermoelectric refrigerator.

15. BUNSEN, R. **On some thermoelectric piles of great activity.** *Phil. Mag.* **29**: 159–162, 1865.

A thermocouple of copper pyrites and copper produces an emf of approximately 0·1V. One junction is heated by a flame, the other is cooled in water.

16. Carnegie Institute of Technology, College of Engineering and Technology, Atlanta, Ga. **Fundamental research.** 111 p., Dec. 1959.

Abstracts of current research investigations include thermoelectric systems, p. 48; conductions of electricity by thin metallic films, p. 49; and studies in electrical energy converters, p. 49–50.

17. CELENT, CHRISTOPHER. **Thermoelectricity—the state of the art.** *Electron. Indus.* **18**: 66–78, illus., Jly. 1959.

The century-old thermoelectric principle is no longer a curiosity relegated to the back of the physics books. New materials and methods of fabrication are producing laboratory devices which prove the feasibility of thermoelectricity for power generation and cooling. Readily adapted to a host of new situations, the devices may furnish auxiliary power for satellites, control the temperature of critical electronic equipment or efficiently utilize "unconventional" power sources such as solar and nuclear energy.

18. **Ceramic compounds generate electricity; thermoelectric ceramics.** *Mat. Design Eng.* **48**: 158, 160, 162. illus. Nov. 1958.

Concerns thermoelectric ceramics—ceramics that can convert the heat of a burning fuel or other high temperature source of heat directly into electricity.

19. **Ceramics can convert heat into electricity.** *Chem. Eng.* **65**: 82, Dec. 15, 1958.

Refers to Westinghouse discovery of a class of thermoelectric ceramics that look promising as an economical means of converting heat directly to electricity on a limited scale without going through the conventional steam-generation cycle.

20. COELHO, R., GODEFROY, L. and TAVERNIER, J. **Quelques problemes abordes par le groupe de recherches sur les semiconductors.** *Rev. Gen. Elec.* **68**: 180L–187L, Dec. 1959.

In French.

Information is given on research in thermoelectricity in France.

21. COOPER, J. C. and FRANKENBERGER, NORBERT. **Thermoelectricity—a ray from the brighter tomorrow.** *Am. Soc. Nav. Engrs. J.* **71**: 657–664, figs., Nov. 1959.

Background information, and explanation of the principle of thermoelectricity, applications, and brief mention of the extensive research and development programme now underway.

22. CRUSSARD, C. and AUBERTIN, F. **Contribution to the study of the thermoelectric power of metals.** *Rev. Mét.* **45**: 402–410, Oct. 1948.

In French.

The thermoelectric properties of the pure metals Cu, Al, Fe, Ni were measured at low temperatures, and the effects of elastic and plastic distortion investigated. In the case of Cu a linear relationship between thermoelectric power and elastic extension was found. The effect of plastic distortion on metals with cubic structures was attributed to hardening. The investigation of the effect of small quantities of impurity in Al and a study of an Al–Cu (4% Cu) alloy led the authors to suggest that the method has metallographic applications, *e.g.*, the accurate tracing of equilibrium diagrams in the region of very small concentrations of elements with very limited solubility.

23. CUSACK, N. and KENDALL, P. **The absolute scale of thermoelectric power at high temperature.** *Phys. Soc. Proc.* **72B**: 898–901, Nov. 1, 1958.

The object of the note is to point out that a combination of measurements now available in the literature enables the absolute thermoelectric power scale to be extended to high temperatures, and to provide tables of S for each of several high melting point metals.

24. CUSACK, N. **Thermoelectricity in metals.** In *The Electrical and Magnetic Properties of Solids*, Ch. 5, p. 97–121, London, Longmans, 1958.

Introductory text on: Seebeck effect, Peltier effect, Thomson effect, thermodynamics of thermoelectricity, an alternative derivation of Kelvin equations, the absolute scale of thermoelectric power, thermoelectric effects and the electron gas model, the perturbed distribution function.

25. DE BIASI, VICTOR. **Undersea weapon systems. Propulson.** *Space/Aero.* **33**: 68–71, illus., Jan. 1960.

Dual use of a thermoelectric system for refrigeration and for generation of electric power is referred to in this review of the latest concepts of underwater propulsion for submarines and missiles.

26. DOUGLAS, R. W. **Semiconductors: no man's land between metals and insulators.** *Nature*, **175**: 1059–1061, June 18, 1955.

Knowledge of basic physics of semiconducting materials has led to development of new circuit devices.

27. DUNLAP, W. C., Jr. **A scientific tour through the soviet union.** *Elec. Eng.* **77**: 1027–1031, Nov. 1958.

Includes brief mention of work in the thermoelectric field by Soviet scientists.

28. DUNLAP, W. C., Jr. **Semiconductor research in the USSR.** *Phys. Today*, **11**: 14–21, May 1958.

In this account of a trip made last year by an American physicist to Soviet Russia, during which he visited several of the important semiconductor research institutes and interviewed a number of Russian scientists, it is pointed out that in the theoretical area, and in such specialized areas as the thermoelectric devices the Russian work stands out.

29. **Foresees expanded use of thermoelectric materials in homes by 1965.** *Prod. Eng.* **30**: 19, Nov. 2, 1959.

Predictions were made at a seminar in thermoelectricity staged by Whirlpool Corp. at which new appliances were shown.

30. **From teakettle to atomic electricity.** *Life*, **46**: 63–64, illus. Feb. 2, 1959.

An old principle plus new materials makes a compact generator for satellites. Heat from current—or vice versa.

31. FUSCHILLO, NICHOLAS. **Thermoelectric energy conversion in solids.** *Frank. Inst. J.* **267**: 443–452, May 1959.

A state-of-the-art article.

32. GARDNER, A. R. **Taming tomorrow's power sources.** *Prod. Eng.* **30**: 28–31, May 4, 1959.

Mentions thermoelectric devices and includes ONR diagrams of thermoelectric principles.

33. General Electric Co. Aircraft Accessory Turbine Department. **Research and development program on thermoelectric conversion of energy.** Final Report, 1 October 1958–30 September 1959. 1 in. thick, Oct. 23, 1959. (Contract DA44-177-TC-525).

Reports major results and conclusions in the materials investigations and systems studies part of the programme. As a final report, it includes a correlated presentation of all pertinent material contained in the eleven previous monthly interim reports which have been prepared during the course of the programme.

Several appendices give additional information, e.g., Appendix A—Fundamental relations for the performance of thermoelectric generators; Appendix B—Relations for efficiency and weight of a thermoelectric generator with heat leakage through insulation—limiting case; Appendix C—Derivation of fundamental relations for the performance of thermoelectric generators.

In the Materials investigation the chalcopyrite-type compounds were selected for investigation, typical examples being $CuGaS_2$, $CuGaSe_2$, $CuGaTe_2$ and the corresponding silver compounds of gallium sulfide, selenide, and telluride.

34. General Electric Co., Syracuse, N.Y. **Study of thermoelectric generator materials,** by N. SCHWARTZ and W. J. VAN DER GRINTEN. 46p., illus., 1959. (Interim Rept. 1) (Contract DA 30-115-ord-960) (AD-217 234)

The technical effort described includes the results of a survey of existing thermoelectric generator elements, calculations on hybrid constructions of thermionic and Seebeck converters (Thermion-Seebeck converters), and work to date on an experimental programme designed to yield high temperature thermal conductivity data of reasonable accuracy on materials of interest in thermoelectric conversion.

35. GENIN, G. **Direct transformation of heat into electric power. The thermoelectric phenomenon.** *Chaleur & Indus.* no. **404**: 59–71, Mar. 1959.

In French. Not examined.

"Historical background of thermoelectricity; results obtained in Russia with the Peltier effect; research of the Westinghouse Electric Co., characterization of the thermoelectric materials according to their parameters; physical interpretation of thermoelectricity, selection of wide and of narrow band materials; future prospects." (*Batelle Tech, Rev.* **8**: 446a, Aug. 1959).

36. **Get set for the shock of thermoelectricity.** *Steel*, **146:** 57–60, figs., Feb. 29, 1960.

It will make obsolete some present products, open new markets, shift others. It will challenge the designer's imagination. It will demand new production processes, new materials, new technology. It will pave the way for new standards of reliability and efficiency. Metal-working will benefit.

37. GETTINGS, HAL. **Prospects for thermoelectricity.** *Missiles & Rockets*, **5**: 29–31, illus., June 22, 1959.

Heavy investment in research gives hope for long-lived power units for space application.

38. GOLDSMID, H. J. **Thermoelectric applications of semiconductors.** *J. Electron.* **1**: 218–222, Sept. 1955.

A review of the theory of thermoelectric generators and refrigerators suggests that materials of high mean atomic weight should be used, provided that the effective mass of the free charge carriers is reasonably high. Results of cooling experiments using Bi_2Te_3 are described and a photograph of a p–n type Bi_2Te_3 couple capable of 40°C cooling is given.

39. GRIER, M. B. **Wide use foreseen for applied thermoelectricity.** *Space/Aero.* **31**: 46–47, 49–50, 52–54, illus., Jan. 1959.

R&D engineers at Nortronics Division, Northrop Aircraft, Inc., Hawthorne, California, are turning up ways to relate the Seebeck and Peltier effects to modern designs in such areas as environmental conditioning, solar power conversion and electronics cooling.

40. GRIFFITH, M. V. **Power from the sun: thermoelectric generation of direct current from solar radiation.** *Direct Curr.* **2**: 47–50, Sept. 1954.

Latest state of development in direct conversion of solar energy into electric power; collection of solar radiation; utilization of absorbed solar

radiation; photoelectric generation of power, thermoelectric generators.

41. GRIFFITH, M. V. **Thermoelectric generation of useful power: a review of the possibilities.** *Direct Curr.* **1**: 10–13, June 1953.

Efficiencies, possible materials, and uses of thermoelectric generators.

42. **Heat into electricity.** *Sci. Am.* **199**: 58–60, Nov. 1958.

Comments, briefly, on recent thermoelectric developments at Westinghouse and the Massachusetts Institute of Technology.

43. **Hot stuff, and cold.** *Newswk.* **53**: 85, Mar 30, 1959.

A popularly styled article about the beginnings of thermoelectric power, its present state and future possibilities.

44. HOWARD, R. E. and LIDIARD, A. B. **Thermoelectric power of ionic crystals.** *Faraday Soc. Disc.* **23**:113–131, 1957.

The thermoelectric power of an ionic conductor MX fitted with electrodes of metal M is discussed from the point of view of the lattice defects existing in the salt. This power is composed of 2 parts: (1) a "homogeneous" part that is related to the "heats of transport" of the defects, and (2) an "inhomogeneous" part that is related to the entropies of formation of the defects. Detailed results are given for the case where MX is a cationic conductor showing Frenkel disorder, and the influence of impurities of type NX_2 in MX is discussed. The power of an impure crystal is found to be unaltered by the establishment of a Soret concentration gradient. Agreement between present theory nad the existing, rather scant, data on AgBr is adequate, but further experiments on AgBr and AgCl are desirable.

45. HOWARD, R. E. and LIDIARD, A. B. **Thermoelectric power of ionic conducting crystals.** *Phil. Mag.* **2**: 1462–1467, Dec. 1957.

The thermoelectric power, θ, of crystals which conduct electricity by movement of Frenkel or Schottky defects is analysed in terms of the concentration of defects, their mobility and their heat of transport. Particular attention is given to AgCl and AgBr containing divalent impurity ions, and isothermals showing the dependence of θ on foreign ion concentration c are constructed. The power increases (algebraically) in proportion to c at small concentrations, reaches a maximum and then slowly decreases with further addition of impurity; the overall changes in θ are $\sim$1 mv/deg.C.

46. HUTH, J. H. **What power sources in space?** *Astronautics* **3**: 24–25, 62–64, illus., Oct. 1958.

Forecasts use of certain oxidic materials, such as ferrites and titanates which may exhibit desirable thermoelectric properties at temperatures as high as 600–1000°C.

47. Infosearch. Technical Literature Information Service, Russian Literature Survey, London, Eng. **Semi-conductor thermoelectric generators and refrigerators and their applications.** $\frac{1}{8}$ in. thick, Aug. 1956 (SEM-1-56).

Six pages of bibliography of literature on semiconductors, their properties and applications is given at the end of the volume.

48. Infosearch. Technical Literature Information Service. Russian Literature Survey, London, Eng. **Semi-conductors for thermoelectric applications.** $\frac{1}{4}$ in. thick, June 1958. (SEM-5-58).

For translations included see Gordyakova, Nikitin, Boltaks, Kolomoets, Semenkovich, Stil'bans, Amirkhanov, and Bashirov.

49. Infosearch. Technical Literature Information Service. Russian Literature Survey, London, Eng. **Soviet progress in semiconductors.** $\frac{3}{4}$ in. thick, Dec. 1957. (SEM-4-57).

Contains translations of five articles.

50. Infosearch. Technical Literature Information Service. Russian Literature Survey, London. Eng. **Thermoelectric applications handbook.** 84 p., Nov. 1958. (SEM-6-58).

Reviews theory of thermoelectric applications; selection, preparation and properties of thermoelectric materials; and measurement of thermoelectric properties. Reports progress in thermoelectric materials made in Russia since 1957.

51. INMAN, B. D. **Thermal generation of electricity and thermoelectric heat pumps.** *Armed Forces Chem. J.* **13**: 20–21, Nov/Dec. 1959.

This is a brief resume of the Navy's thermoelectricity programme and a forecast of important special purpose military applications for thermal electricity.

52. International Conference on Semiconductors, Amsterdam, 1954. **Proceedings . . . 29 June–3 July 1954,** p. 801–1138, Amsterdam, Netherlands Physical Society, 1954.

Reprinted from *Physica*, 1954. For articles specifically on thermoelectricity see entries for AUSTIN, I. G., DONOVAN, B., KRÖGER, F. A., MACDONALD, D. K. C. and SMITH, R. A.

53. International Conference on Low Temperature Physics and Chemistry. **Proceedings . . . 5th Conference,** Madison, Wisconsin, August 1957. 676 p., Madison, University of Wisconsin, Press, 1958.

Among the subjects covered are thermal and electrical conductivity of elements and compounds; thermal and electrical conductivity of alloys; magneto-resistance, thermoelectricity, resistivity, and Hall effect.

See entries for Bunch, Hall, MacDonald and Roder.

54. International Conference on Semiconductors. **Proceedings.** Rochester, August 18–22, 1958. 552 p., illus., New York, Pergamon Press, 1959.

Published as Physics and Chemistry of Solids, **8**, January 1959.

For individual entries, see Appel, Joffe, Hutson, Kanai, Roder, Sasaki, and Zener.

55. IOFFE, A. F. **The revival of thermoelectricity.** *Sci. Am.* **199**: 31–37, illus., Nov. 1958.

The Seebeck and Peltier effects dispense with moving parts in the transformation of energy from heat to electricity. Long regarded as curiosities, they are now generating a technological revolution, due to the semiconductor.

56. IOFFE, A. F. **Semiconductor thermoelements and thermoelectric cooling.** 184 p., illus., London, Infosearch Limited, 1957.

Translated from the Russian.

Part 1, Ch. 1, Introduction: Ch. 2, Thermoelectric generators; Ch. 3, Other applications of thermoelements. Part 2, Ch. 1, Theory of thermoelectric cooling; Ch. 2, Experimental investigation of the thermoelectric properties of semiconductors; Ch. 3, Applications of thermoelectric cooling.

57. IOFFE, A. F. **Thermoelectric and thermal properties of semi-conductors.** *J. Phys. et Radium*, **18**: 209–213, Apr. 1957.

Discussion with reference to the application of semiconductor thermocouples for power supply.

58. IOFFE, A. F. and STIL'BANS, L. S. **Physical problems of thermoelectricity.** *Rept. Prog. Phys.* **22**: 167–203, 1959.

The interest in thermoelectric phenomena and in their practical applications led to an investigation of semiconductors with high electrical conductivities σ and low thermal conductivities k. The requirement of the highest possible ratio of the mobility U to k directed attention to solid solutions. k could be decreased to values corresponding to a free path of phonons of a few interatomic distances. The replacement of positive ions in a compound by analogous ions (for instance Bi by Sb in Bi_2Te_3, or Pb by Sn in PbTe) decreases many times the mobility of electrons, while the mobility of holes remains unaltered. A distortion of the sublattice of negative ions leads to a decrease of the mobility of holes. The influence of impurities on the free path of phonons and of free charge carriers reveals the scattering cross-section of defects. Crystal lattices with a proportion of unfilled sites have exceptionally short free paths which, calculated in the usual way, are smaller than the periods of the lattice. Accordingly the mobility increases with rising temperature; using degenerative systems of free charge carriers it became possible to separate the influence, on the mechanism of scattering, of the velocity of electrons on one hand, and of the thermal motion of the lattice on the other. The onset of intrinsic conduction introduces an additional thermal conductivity due to the diffusion of electron-hole pairs. Excitons, with small excitation energies, have an analogous effect. The high transparency of pure semi-conductors to radiation with hv*w*E° brings into action a heat conduction mechanism, due to the transmission of infrared radiation, as long as absorption by impurities or by free charges does not stop the radiation. The dragging of phonons and electrons increases both the thermal conductivity and the thermoelectric power at low temperatures. The materials selected for thermoelectric devices are investigated in detail.

59. IOFZE, A. F. **Poluprovodniki i ikh primenenie. (Semiconductors and their application).** 63 p., Moscow, Znanie Publishing House, 1956.

In Russian.

Two lectures on the properties and applications of semiconductors: I—The Physics of Semiconductors; II—The Application of Semiconductors in Industry and Life.

60. IOFFE, A. F. **Semiconductor materials for thermoelements.** *In* Infosearch Ltd. Semiconductor Heat and Light Energy Converters, p. 1.1–1.11, London, Jan. 1959. (*Russian Lit. Survey*, SEM–7–59).

Describes materials which have been used until now for the construction of thermoelements.

61. IOFFE, A. F. **Thermoelectricity in semiconductors.** *Zhurn. Tekh. Fiz.* **23**: 1452–1459, 1953.

In Russian.

Problems involved in obtaining TE generators of high efficiency discussed. Maximum efficiency is: $p=(T1—T2)/T1[1+(2/A) \quad (1-\sqrt{1-A})]$ where $A=T_1(a_1+a_2)-{}^2/(r_1+r_2)\,(x_1+x_2)$, where a is the TE force, r the specific resistivity, and x the thermal conductivity. The dependence of a, r, and x on T is little known and requires more theoretical study.

62. IOFFE, A. F. **Unsolved problems of the semiconductor theory.** *Akad. Nauk. SSSR. Ser. Giz-Izvest.* **15**: 477–486, 1951.

Existence of liquid semiconductors makes present theory, based on periodicity of the crystal lattice, inadequate. Examples are given of the semiconducting nature of liquids: the temperature coefficient of conductivity of T1°S, Sb°O°, Bi°O°, Na°Te° remains the same in the solid and liquid state; however, when fusion is accompanied by a change in the nature of chemical bonds or coordination number (Ge, Se), there is an abrupt change in conductivity and temperature coefficient. Ge becomes metallic, Se remains a semiconductor with an enlarged forbidden zone; liquid Te gradually goes from a semiconductive to a metallic state. The movement of electrons in the crystal is not a function of m_0 (mass of free electron) but of M* ("effective" mass of the electron). The M* can be calculated from simultaneous measurements of the Hall constant and TE force. It is tabulated for diamond type lattices (Si–p, Si–n, Ge–n, HgSe–n, HgTe–n, InS–bp) and shows that the "effective" mass is equal to the "free" mass for Si–p, Si–n, InS–bp, and HgTe–n; is a small fraction of this mass in Ge–n, HgSe–n, PbTe–n, and CdTe–n; and is many times greater in TiO_2–n, Wo_3–n, and Se–p. Metals can also have "hole" conductivity, or mixed electron and hole conductivity.

63. JAUMOT, F. E., Jr. **Thermoelectric effects. Appendix I—derivation of the Kelvin relations. Appendix II—useful formulas for practical applica-**

tion of thermoelectric effects. *Inst. Radio Engrs. Proc.* **46**: 538–554, Mar. 1958.

Review of the basic principles of thermoelectric effects in solids, with emphasis on the practical application of these effects. The present status of the problem and recent achievements are outlined. A qualitative approach is used.

Includes over 100 references.

64. JOHNSON, MATTHEY AND CO., Hatton Garden, London. **Semiconductors: an introduction to principles, materials and uses.** 12 p., May 1959.

Pamphlet. Concise account covering semiconductor devices; diodes and rectifiers, transistors (point contact, junction and photo-), Hall effect devices (thermoelectric refrigeration and power generation). Not examined.—(*Brit. Non-Ferrous Metl Res. Assoc. Bull. No.* **363**: 492, Oct. 1959).

65. JUSTI, E. **Electrothermal refrigeration.** *Kältetechnik*, **5**: 150–157, 1953.

A summary of the theoretical, experimental, technical and economic aspects of the Seebeck, Peltier, and Thomson thermoelectric effects.

66. KELLY, J. **Explanation of the mechanism of thermoelectric refrigeration.** *Air Cond. Heat and Vent.* **56**: 89–91, Mar. 1959.

Basic principles of thermoelectricity to provide better understanding of production of cold through this principle are discussed. Thermoelectric refrigeration is defined as heat pumped by electrons. Materials found most attractive are those in the general class of semiconductors. Thermal efficiency, coefficient of performance is defined as heat being pumped divided by power necessary to pump it; this may be related to properties of material by given expression.

67. KELLEY, C. M. **Thermoelectric power.** *In* International Symposium on High Temperature Technology, October 6–9, 1959. Advance Papers, p. 328–337, Stanford, Calif., Stanford Research Institute, 1959.

Considers the status of knowledge of thermoelectric theory and the development of thermoelectric devices.

68. KELLY, J. C. R., Jr. **This business of getting power direct from heat, where does it stand today?** *Power Eng.* **63**: 73, Jly. 1959.

Remarks taken from a paper presented at the 1959 American Power Conference.

Briefly compares the mechanism of thermoelectricity with conventional power generation.

69. KELLY, J. C. R., Jr. **Direct conversion of heat to electric power. Its present status and future prospects.** *In* American Power Conference Proceedings vl. XXI, p. 45–50, Chicago, Illinois Institute of Technology, 1959.

A summary article including the history, physics and engineering of thermoelectricity; the state of the art; percentage of efficiency; heat pumps; and a forecast

70. KHALILOV, A. YU. **Study of temperature dependence of thermoelectromotive force of semiconductors.** *Azerbaid. Zaoch. Pedagog. Inst. Trudy. No.* **1**: 69–78, 1954.

In Russian. Not examined.

"Specimens of Cu_2O, MoS_2, PbS were tested in order to find the dependence of thermo emf on temperature. Butts of specimens were submitted to a temperature difference of 773°K. It was found that the thermo-emf of all tested semiconductors increases with rising temperature." *Referat. Zhurn. Fiz. No.* 14208, 1955.

71. KLASS, P. J. **Arpa studies auxiliary space power.** *Aviat. Wk.* **71**: 89–91, 93, 95, 97, Jly. 13, 1959.

Briefly lists some of the industrial concerns actively investigating means for generating electric power, and describes their objectives. Merck, Sharp & Dohme Research Laboratories, a pharmaceutical house, is said to be producing thermoelectric materials such as bismuth telluride and is developing improved semiconductor materials for this purpose.

The article also indicates some of the more promising possibilities for electric power systems for space vehicles, among them the solar thermoelectric system, solar thermionic system, and the nuclear thermoelectric system.

72. LAFOND, C. D. **How NBS researches semiconductors.** *Missiles and Rockets*, **5**: 31–33, illus., Apr. 27, 1959.

The study of electrical measurements includes investigation of the thermoelectric effect.

73. LANGE, ERICH. **The galvanic thermocell: the thermocouple.** *Z. Physik. Chem.* **209**: 162–178, 1958.

In German.

For English summary see *Chem. Asb.*, **53**: 19634, 1959.

74. LANGENECKER, B. **Zum problem der rationellen thermoelektrischen stromerzeugung im extraterrestrischen aufgabenereich. (On the problem of a practical thermoelectric current generator for extraterrestrial applications).** *In* International Astronautical Congress, 4th, Zurich, 1953, *Space Flight Problems*, p. 181–188, Biel-Bienne, Switzerland, Laubscher, 1953.

In German.

An account of the principles of thermoelectricity and their applications.

75. LIEBERMAN, D. S. **Thermoelectricity. A conference report.** *Phys. Today* **12**: 26–28, Feb. 1959.

A summary of some of the papers given at the Conference on Thermoelectricity conducted by the U.S. Naval Research Laboratory in Washington, D.C., on September 3 and 4, 1958.

76. MACDONALD, D. K. C., MOOSER, E., PEARSON, W. B., TEMPLETON, I. M. and WOODS, S. B. **On the possibility of thermoelectric refrigera-**

tion at very low temperatures. *Phil. Mag.* **4**: 433–446, illus., Apr. 1959.

Considered here is the problem of thermoelectric refrigeration at very low temperatures, in particular for the attainment of temperatures below 1°K.

77. MACDONALD, D. K. C. **Thermoelectricity at very low temperatures.** *Sci.* **129**: 943–949, figs., Apr. 1959.

Considers the significance of recent experimental work on thermoelectricity at low temperatures. The author believes that Kelvin's discovery may be the key today to electron transport problems.

78. MACDONALD, D. K. C., PEARSON, W. B. and TEMPLETON, I. M. **Thermoelectricity at low temperatures.** *In* International Conference on Low Temperature Physics and Chemistry. Proceedings, 5th, 1957, p. 481–484, Madison, University of Wisconsin Press, 1958.

A brief review of investigations undertaken by the authors since 1952.

79. MANCHESTEF, HARLAND. **Electricity direct from heat.** *Popular Mech.*, **111**: 93–96, May 1959.

The thermoelectric engine makes its debut—a versatile new power maker is moving in, one which bids fair to have a profound effect on the world's technology.

Condensation in *Reader's Dig.*, **75**: 212–213, 215–216, illus., Jly. 1959.

80. Martin Co., Nuclear Division, Baltimore, Md. **Strontium-90 programme.** 2 p., Oct. 1958. (Rept. MND–SR–1530–1) (*Mon. Prog. Rept.* 1).

Systems investigation to date indicates that the most reliable scheme for converting heat to electrical power would be by using a thermoelectric conversion system. Examination of the problems of radiation damage to such a system are in progress. Preliminary evidence indicates that there would be no detectable damage by gamma radiation to a direct conversion system in ten years of operation. A more detailed examination of this problem will be made.

81. Martin Co., Nuclear Division, Baltimore, Md. **Power from radiosotopes,** by *K. P. Johnson.* 18 p., 1958. (*Rept. AECU–4373*).

Available from OTS.

The relative power producing capabilities of several isotopes are considered and their present costs and availability are discussed. Their use for power production in the near future should be considered only for special applications where an extremely dependable source of heat coupled with a simple power conversion system is required.

82. Massachusetts Institute of Technology. Research Laboratory for Electronics, Cambridge, Mass. **Quarterly progress report No. 51.** 123 p., Oct. 15, 1958. (Contract DA36–039–sc–64637).

Thermoelectric processes and materials, p. 40.

83. Massachusetts Institute of Technology. Research Laboratory of Electronics, Cambridge, Mass. **Quarterly progress report No. 54.** 201 p., Jly. 15, 1959. (Contract DA36–039–sc–78108).

Thermoelectric processes and materials: (A) Anisotropic thermoelectric effects, 1. Experiments with bismuth telluride. (B) Thermal conductivity studies. (C) Transport of contact materials in bismuth telluride.

84. Massachusetts Institute of Technology. Research Laboratory of Electronics, Cambridge, Mass. **Quarterly progress report No. 55.** 170 p., Oct. 15, 1959. (Contract DA36–939–sc–78108).

Thermoelectric processes and materials (anisotropic thermoelectric effects—theory, experiment; transport of contact materials in bismuth telluride; thermal conductivity studies), p. 48–50.

85. Massachusetts Institute of Technology. Electronic Systems Laboratory, Cambridge, Mass. **Theoretical and experimental research in thermoelectricity.** 150 p., Dec. 31, 1959. (Sr–1–AFCRC–TN–60–125) (Contract AF19(604)–4153).

Discusses techniques and equipment for growing single crystals of Bi_2Te_3; equipment for measuring parameters of thermoelectric materials; measurements; and theoretical analysis of devices.

86. Massachusetts Institute of Technology. Research Laboratory of Electronics, Cambridge, Mass. **Quarterly progress report No. 53,** 211 p., *illus.*, April 15, 1959.

Thermoelectric processes and materials (anisotropic thermoelectric effects, theory, experiments with bismuth telluride); thermal conductivity studies, p. 34–38 (Contract Nonr–1841(51)).

87. Massachusetts Institute of Technology. Research Laboratory of Electronics, Cambridge, Mass. **Quarterly progress report No. 56.** 255 p., Jan. 15, 1960. (Contract DA36–039–sc–78108).

Thermoelectric processes and materials (mercury telluride evaluation; thermoelectric temperature control of electronic components; transport of contact materials in bismuth telluride; thermal conductivity studies), p. 72–75.

88. **Materials for Peltier cooling.** *Battelle Tech. Rev.*, **8**: 14, Mar. 1959.

Relates plans at Battelle Memorial Institute for research to broaden science's knowledge of materials and techniques required for thermoelectric cooling devices. Initially, the two-year programme is being sponsored by 16 American industrial firms interested in research basic to the use of the so-called Peltier cooling effect for refrigeration.

89. MAYCOCK, P. D. **Thermoelectricity: power hope for tomorrow?** *Res. Revs.* (*ONR*), p. 1–5, *illus.*, Nov. 1958.

Indicates thermoelectric possibilities and mentions the ONR programme devoted to fundamental aspects of the problem. Lists locations where experimental and theoretical studies are being conducted.

90. MAYER, E. F. **Powerhouse in a capsule.** *Mach. Design*, **31**: 22–27, Apr. 2, 1959.

Briefly discusses current research on thermoelectric sources. Recently announced devices include a thermoelectric generator developed by Horizons, Inc., for the Rome Air Development Centre, and SNAP-III. These thermoelectric generators are solid-state devices, and operate at relatively low temperatures compared to thermionic converters, but at high temperatures compared to, for example, a hydrogen-oxygen fuel cell system.

91. **More efficient thermoelectric materials.** *Eng. Mat. & Design*, **2**: 481–482, Oct. 1959.

"A discussion is presented of the thermoelectric properties of some materials. A brief description of a plasma cell is included." (Instr. Abs. **14**: 533, Dec. 1959).

92. MORGULIS, M. S. **A new thermoelectric phenomenon.** *Elektrichestvo* **9**: 59–60, 1957.

In Russian.

A thermo-emf is set up in a homogeneous wire when a temperature gradient existing in it is displaced, *e.g.*, a flame is moved along the wire. The emf increases with the speed of displacement and changes sign when the direction of displacement is reversed. Heavier currents are set up in thinner wires, which heat and cool more rapidly.

93. Naval Ordnance Laboratory, White Oak, Md. **Report of a trip to european laboratories and meetings,** by R. L. PETRITZ. 25 p., Jly. 30, 1958. (BuOrd, NAVORD Rpt. 6161).

Thermoelectric power programmes underway at Ecole Normale Superiere, Paris, France, are mentioned on p. 15.

94. Naval Research Laboratory, Washington, D.C. **Status report on thermoelectricity,** by H. E. STAUSS in collaboration with B. B. ROSENBAUM (BuShips) and P. MAYCOCK (ONR), 127 p., 1959(?) (*Memo Rpt.* 901).

This report, which is largely restricted to a description of current efforts in the United States, is the first of what is planned to be a quarterly review of the state of the art in thermoelectricity.

Background information is given as to needs and possible applications; and the government and industry sponsored programmes are outlined. Three appendices are included: Appendix I, Thermoelectric Power Generation; Appendix II, State of the Theory of Thermoelectricity; and Appendix III, Government Contracts Dealing with Thermoelectric Power Generation and Peltier Heat Pumping.

95. Naval Research Laboratory, Washington, D.C. **Status report on thermoelectricity,** by H. E. STAUSS, B. B. ROSENBAUM, P. D. MAYCOCK and J. C. COOPER. 52 p., figs., June 1959. (*Memo Rept.* 940).

In the second status report the material presented consists of: (1) the power-to-weight ratios of several thermoelectric generators, (2) the characteristics of thermoelements cooled by radiation, (3) the effect of increasing temperature upon efficiency, (4) materials data, and (5) changes and corrections in contracts.

96. Naval Ordnance Laboratory, White Oak, Md. **A survey of basic research in thermoelectricity,** by W. W. SCANLON. 11 p., June 1, 1959. (*Rept.* 6663) (AD–220–241).

The present status of research in the general area of thermoelectricity was surveyed for the purpose of evaluating the present understanding of the phenomena and to point out areas where additional knowledge is needed. Thermoelectric effects were considered in metals and insulators as well as in semiconductors. As a result of this study it is apparent that even in the simplest monatomic metals such as the alkali metals, the theory is unable to account qualitatively or quantitatively for the observed behaviour. Wide discrepancies are found in some of the metals which are generally believed to approximate closely the ideal free electron behaviour.

97. Naval Research Laboratory, Washington, D.C. **Experimental verification of thermoelectric theory,** by DANIEL FRIEDMAN. 9p., figs., Jan. 1960. (Letter Rept. 5230–47).

The design and performance of a unit which can be used to provide an experimental verification of thermoelectric theory and/or to measure the thermoelectric properties of materials is described. Using doped bismuth telluride p- and n-type materials (at approximately room temperature), the following results were obtained: The experimentally determined values of the Peltier effect agreed with the theoretical values within the limits of experimental error. The electrical resistance of p- and n-type thermoelectric material were measured by d.c. and a.c. methods and the results agree within the limits of experimental error. The magnitude of the Seebeck and Thompson effects were measured. The predicted performance of the thermoelectric unit in the three modes of operation (refrigeration, heat pump, and power generation) showed good agreement with the experimentally measured performance. Some of the effects of high contact resistance are discussed and recommendations for additional research outlined.

98. Naval Research Laboratory, Washington, D.C. **Status report on thermoelectricity,** by H. E. STAUSS, B. B. ROSENBAUM, P. D. MAYCOCK and J. C. COOPER. 76 p., figs., Dec. 1959. (Memo Rept. 969).

This, the third report in a series of quarterly reviews, includes discussions on thermoelectricity with high energy radiation; materials data (liquids and encapsulated solids, III-V compound semiconductors, chalcopyrite and related structures, Westinghouse materials data); and government contracts dealing with thermoelectric power generation and Peltier heating.

An appendix gives Russian Use of Thermoelectricity, a survey made by Captain N. Frankenberger.

99. Naval Research Laboratory, Washington, D.C. **Status report on thermoelectricity,** by J. W. DAVISON and JOSEPH PASTERNAK in collaboration with B. B. ROSENBAUM, J. C. COOPER and P. D. MAYCOCK. 180 p., Mar. 1960. (Memo Rept. 1037).

This is the fourth report in a series of quarterly reviews. In it progress to date, is reviewed. Materials development is indicated by a series of figures including data resulting from extensive investigations at Westinghouse. Materials data on a number of ternary compounds investigated by Bell Telephone Laboratories, RCA, Stanford, and National Carbon Research Laboratories is also given.

All contracts are listed, together with a brief description, a report of progress and a record of published reports.

Appendix I is entitled "Thermoelectric Refrigeration Studies by Whirlpool Corporation under Contract Nobs 77128" and was prepared by A. F. Phillips.

100. **New ceramic type thermoelectric materials.** *Engrs. Dig.* **19**: 509, Dec. 1958.

Refers to recent announcement of new thermoelectric materials.

101. **New hot-cold light panel has space use.** *Missiles and Rockets.* **4**: 29, Oct. 27, 1958.

The Westinghouse experimental panel combines two new technological advances—thermoelectric refrigeration and electro-luminiscent lighting. The system might be used in satellites and space vehicles for cooling and heating electronic machinery in space.

102. **New materials to convert heat to electricity.** *Westinghouse Engr.* **18**: 190, Nov. 1958.

Refers to thermoelectric materials and their possible uses.

103. NOON, J. H. and O'BRIEN, B. J. **Sophomore experiment in thermoelectricity.** *Am. J. Phys.* **26**: 373–375, figs., Sept. 1958.

A laboratory experiment is described in which the temperature change caused at the junction of two metals is studied for both directions of current through the junction. It extends the usual thermocouple-calibration experiment and encourages consideration of thermoelectric cooling as a possible source of refrigeration.

104. Office of Naval Research, Washington, D.C. **Thermoelectric converters.** 18p., July, 1958.

Report by the ONR Committee on Thermoelectric Power includes status of thermoelectric conversion in the U.S. (including brief report of work at various laboratories) and discussion of some technical questions.

105. **Organization of USSR work on thermal elements.** *Akad. Nauk. SSSR Vest.* **29**: 74, Aug. 1959.

"Attaching particular attention to the organisation of scientific research work in the development of thermoelements with a high efficiency, the Presidium of the Academy of Sciences USSR resolved to organise, at the Electrophysicsl Laboratory of the Institute of Metallurgy imeni A. A. Baykov, theoretical and experimental research on scientific and technical problems pertaining to thermoelectronic conversion and to the creation of thermoelectric devices which operate on the cascade principle and have a high efficiency."

106. PEARSON, W. B. and TEMPLETON, I. M. **Thermoelectricity at low temperatures. III. The absolute scale of thermoelectric power: a critical discussion of the present scale at low temperature and preliminary measurements towards its redetermination.** *Roy. Soc. London Proc.* **231A**: 534–544, Sept. 20, 1955.

In order to compare exactly the present theory of thermoelectric power in metals with the behaviour of the simple alkali metals, particularly sodium, at low temperatures, it is necessary to know the absolute thermoelectric power of one single conductor. In this paper the present absolute scale of thermoelectric force is critically discussed particularly in relation to preliminary measurements towards its redetermination.

107. PEET, C. S. **Semiconductors in industry.** *Batelle Tech. Rev.* **5**: 7–11, Feb. 1956.

Variety and types of changes that occur in semiconducting devices when ambient conditions are varied; table summarising semiconductors and data; uses in fields of detection and measurement; control, and energy conversion; advantages and disadvantages of such devices; promising new areas for semiconductor use.

108. Plasmadyne Corp., Santa Ana. Calif. **Direct electrical converters. Vol. III. Fundamental investigations of electrical power sources,** by E. J. HELLUND. 76 p., Apr. 24, 1959. (Rept. E-3FR049-332) (AFOSR Tech. Note 59–429). (Contract AF49(638)–332).

Thermoelectric devices, p. 23–28.

109. Plasmadyne Corp., Santa Ana. Calif. **Fusion power. Vol. VI. Fundamental investigations of electrical power sources,** by E. J. HELLUND. 74 p., Apr. 24, 1959. (Rept. E-6FR049-332) (AFOSR Tech. Note 59-427) (Contract AF49(638)-332).

Electrical power from thermonuclear fusion, p. 43.

110. Rand. Corp., Santa Monica, Calif. **Utilization of a moon-rocket system for measurement of the lunar magnetic field,** by E. H. VESTINE. 24 p., table, Jly. 9, 1957. (Res. Memo. 1933) (Contract AF 33(038)-6413).

A thermoelectric theory of a lunar field, p. 9.

111. RIAZ, MAHMOUD. **Thermoelectric energy conversion.** *In* Army Signal Research and Development Laboratory. Power Sources Division. Proceedings, 12th Annual Battery Research and Development Conference, p. 116–119, illus., Fort Monmouth, 1958.

Discusses the present state of the art in thermoelectric energy conversion; thermoelectric effects, and efficiency of thermoelectric energy conversion.

112. RUST, A. **Thermoelectricity theoretically and practically considered.** *Elec. World*, **14**: 52, 69, 90, 1889.

An illustrated series of articles discusses the theory of thermoelectric couples and describes many experimental thermocouples. A thermoelectric generator (Magnopile) comprising 60,000 elements generates 96 volts.

113. SCANLON, W. W. **Survey of semiconductor research and development.** *In* Johns Hopkins University. Operations Research Office. Proceedings of the Army-ORO Conference on Basic and Applied Research and Component Development, v. VII, Papers 5, 9, 16 and 27, ed. by J. B. GREEN, p. 5–12, *Bethesda Md.*, Sept. 1959. (ORO-SP-68).

Mentions, briefly, the useful military objectives of thermoelectric generators.

114. SCHULZE, A. **Choice and Behavior of metallic materials for thermoelements.** Elektrotechnik **3**: 65–70, Mar. 1949.

In German.

Materials are described for thermoelements suitable for average (0–600°), high (1000–1200°), and low temperatures, and also for particular objectives such as the measurement of feeble alternating currents and radiation. Problems arising out of the use of friable substances and from combinations of thermoelements are discussed, and the present position at the highest temperatures is reviewed. There are 6 diagrams, and a table of thermoelectric potentials for the materials involved.

115. SHIVE, J. N. **The properties, physics, and design of semiconductor devices.** 487 p., illus., Princeton, N. J., D. Van Nostrand Co., 1959.

Thermoelectric effects in semiconductors, p. 25, 423–439.

116. SMITH, R. A. **Semiconductors.** 494 p., figs., Cambridge, Cambridge University Press, 1959. Thermoelectric power, p. 170–176. Germanium and silicon—thermoelectric power, p. 369–372.

Molten Ge-thermoelectric power, p. 372.

Thermopiles and thermoelectric refrigerators, p. 478–479.

117. SOMINSKII, M. S. **Semiconductor thermoelectric devices.** *Akad. Nauk. SSSR. Vest.* **26**: 14–23, 1956.

In Russian.

Translation in Infosearch Tech. Lit. Info. Serv. Russian Lit. Survey SEM-2–57: 1.1–1.12, 1957.

A review of developments in the Soviet Union.

118. STEELE, GORDON. **What makes a good thermoelectric material?** *Space/Aero*, **32**: 164–168, illus., Nov. 1959.

Electric and thermal conductivities, thermoelectric power are basic parameters; simplified figure of merit has been worked out by Soviet researchers; materials research underway for large and small junction differentials.

119. STIL'BANS, L. S. **Thermoelektricheskiye Yavleniya. (Thermoelectric effects).** Poluprovodniki v Nauke i Tekh. **1**: 113–132, 1957.

In Russian. Trans. no. 59–19482 available from SLA or LC.

Topics discussed include (1) theory of thermoelectric effects, (2) electron entrainment by phonons, (3) procedures for measuring thermoelectric characteristics properties of semiconductors, and (4) a comparison of experimental and theoretical results of studies covering thermoelectric properties of semiconductors and semimetals. (Tech. Trans. **3**: 57, Jan. 8, 1960.)

120. TAUC, JAN. **An explanation of some anomalous thermoelectric phenomena on the surface of transistor materials.** *Czechoslov. J. Phys.* **3**: 259, Sept. 1953.

The anomalous surface layer reported by Granville and Hogarth is considered to arise through deformation of the crystal lattice near the surface, caused by stresses during polishing. By considering an assembly of semiconductor with a surface layer of opposite conductivity type, the reversal of thermoemf of a point contact on warming up the crystal may be explained on the basis of a theory due to Tauc and Trousil.

121. TELKES, MARIA. **The efficiency of thermoelectric generators.** *I. J. Appl. Phys.* **18**: 1116–1127, Dec. 1947.

The generation of electrical energy from thermal energy by thermoelectric means cannot be accomplished with thermocouples made of the available alloys generally used for temperature measurements, their efficiency being less than one per cent.

Higher thermoelectric efficiencies can be produced only by developing new materials which can attain the theoretically required high values of thermoelectric power, low heat conductivity, and low specific resistance.

122. **Thermoelectric cooling.** *Brit. Comm. & Electron.* **7**: 110–112, figs., Feb. 1960.

This article gives a brief account of the theoretical basis of thermoelectric cooling, and reviews the different fields of possible application as seen from the point of view of the General Electric Co., Ltd.

123. **Thermoelectric cooling.** *Eng.* **208**: 734–735, illus., Dec. 4, 1959.

Relates that recent work in the field of semiconductors has resulted in the production of materials that may make thermoelectric cooling feasible on a commercial scale. Some possibilities are outlined.

124. **Thermoelectric power sources.** *Brit. Comm. Electron.* **5**: 864, Nov. 1958.

A satellite power-supply of semiconductor type is one of several unconventional power sources under consideration in the U.S.A.

125. THIEN-CHI, N., VERGNOLLE, J. and DONNADILLE, B. **Conversion d' energie par effet Seebeck et refrigeration par effet Peltier (energy conversion by Seebeck effect and refrigeration by Peltier effect).** *Ann. Radioelec.* **14**: 275–321, figs., Oct. 1959.

In French.

In Part I the authors briefly recall the main general notions relative to thermoelectric phenomena. Part II deals with the general investigation, based on calculations of a thermoelectric couple considered either as an electrical generator, or as a refrigerator using the Peltier effect. Lastly, in Part III, dealing with engineering matters, the authors describe work carried out in the C.S.F. laboratories and give a few results on certain semiconductors.

126. **To heat, to cool, and to light.** *Eng.* **188**: 16, Aug. 7, 1959.

Descriptions and illustrations of Westinghouse ideas on the thermoelectric refrigerator and a wall panel which provides heating as well as lighting.

127. **Toward thermoelectric power.** *Prod. Eng.* **29**: 10, June 30, 1958.

The investigation of the semiconducting chalcopyrites, the copper–iron–sulfur compounds that are structurally related to diamond, for thermoelectric power applications is briefly discussed.

128. U.S. Bureau of Mines, Washington, D.C. **Bibliography on semiconductors for thermoelectric use,** by E. H. ILLSLEY and H. KATO. 28 p., 1959. (Info. Circ. 7910).

The 131 annotated references are grouped in the following categories: general references; Peltier effect; thermoelectric and thermal conductivity theory and related topics; experimental methods, materials and applications; and studies of tellurides and selenides.

129. U.S. Congress, 85th, 2nd Session. Joint Committee on Atomic Energy. **Outerspace propulsion by nuclear energy.** Hearings of the Joint Committees . . . January 22, 23 and February 6, 1958. 232 p., illus. Washington, U.S. Government Printing Office, 1958.

Thermoelectric effects, p. 127.

130. Westinghouse Electric Corp., Pittsburgh, Pa. **Thermoelectric nuclear fuel elements,** by F. L. CARTER, *et al.* 67 p., Nov. 15, 1958. (Quart. Prog. Rpt. 1) (Contract AT(30–3)–500).

Thermoelectric design considerations; Preparation of mixed-valence thermoelectric materials; Thermoelectric property measurements; Physical and chemical characteristics of thermoelectric materials; Irradiation of thermoelectric materials.

131. Westinghouse Research Laboratories, Pittsburgh, Pa. **Thermoelectricity.** ½ in. thick, Feb. 11, 1959. (Quart. Prog. Rpt. 1) (Contract Nobs–77043).

The materials development programme is summarised and mention is made of two pieces of measuring equipment: (1) a device for measuring thermal conductivity up to 1000°C, and (2) an instrument for carefully determining the variation of resistivity along a given element.

Also included is Scientific Paper 431–FD–405–pl entitled $InAs_{1-x}P_x$ as a Thermoelectric Material, by R. BOWERS, J. E. BAUERLE and A. J. CORNISH, dated June 26, 1959.

132. Westinghouse Research Laboratories, Pittsburgh, Pa. **Thermoelectricity.** ½ in. thick, May 12, 1958. (Prog. Rpt. 4) (Contract Nobs–72361).

Limited availability.

Includes Materials Progress Report; Preparative Techniques for Mixed Valence Materials, by P. E. Snyder; Thermal Design by E. V. Somers; and A Study of Several Systems of the Type $Li_x[Co_yNi_{(1-y)}](1-x)^\circ$, by W. D. Johnston, R. C. Miller and R. Mazelsky.

133. Westinghouse Research Laboratories, Pittsburgh, Pa. **Thermoelectricity.** 1 in. thick, June 23, 1958. (Prog. Rpt. 5) (Contract Nobs-72361).

Limited availability.

Includes the following reports: Crystal Growth, by W. A. Tiller, Thermal Diffusion in Thermoelectric Elements, by P. Shewmon; Studies of Polaron Motion I. The Molecular Crystal Model, by T. Holstein; Measurement of Thermoelectric Materials Under Simulated Generator Conditions, by S. J. Angello and C. S. Duncan; Zinc in Metal Oxides, by R. J. Nadalin; and The Use of Controlled Solidification in Equilibrium Diagram Studies, by W. A. Tiller.

134. Westinghouse Research Laboratories, Pittsburgh, Pa. **Thermoelectricity.** ½ in. thick, Jly. 30, 1958. (Prog. Rpt. 6) (Contract Nobs-72361).

Limited availability.

Contents: Materials Progress Report, p. 1–6; Use of Classical Semiconductors in Thermoelectric Devices, p. 7–32; Effect of Impurity Scattering on the Figure of Merit, p. 33–36; Solid–Liquid Phase Equilibria in the Pseudo-binary System Bi_2Te_3–Bi_2Se_3 by J. P. McHugh and W. A. Tiller.

135. Westinghouse Research Laboratories, Pittsburgh, Pa. **Thermoelectricity.** ½ in. thick. Oct. 1, 1958. (Prog. Rpt. 8) (Contract Nobs-72361).

Limited availability.

Report includes (1) Scientific Paper 431FD272-P1, Alloy Crystal Growth, by W. A. Tiller, 17 p., Sept. 18, 1958. (2) Scientific Paper 431FD270-P3, Arc Furnace Preparation of Refractory Compounds, by H. A. Johansen, 14 p., June 11, 1958. (3) Research Memo 403FD211-M2, Studies of Polaron Motion II. The "Small" Polaron, T. Holstein, 29 p., Sept. 26, 1958.

136. Westinghouse Research Laboratories, Pittsburgh, Pa. **Thermoelectricity.** 23 p., Nov. 15, 1958. (Prog. Rpt. 10) (Contract Nobs-72361).

Limited availability.

RM431FD279-M2, Engineering Estimation of Thermal Efficiency in Thermoelectric Power Generators, by C. Zener. RM431FD279-M4(412), Calculation of the Efficiency of a Thermoelectric Device II, by B. Sherman. RR431FD275-R2, Analysis of Bismuth–Antimony–Tellurium–Selenium Combinations, by J. Reed.

137. Westinghouse Research Laboratories, Pittsburgh, Pa. **Thermoelectricity.** $\frac{1}{2}$ in. thick. Nov. 15, 1958. (Prog. Rpt. 11) (Contract Nobs-72361).

Limited availability.

This report collates theoretical and experimental information of thermal conductivity. Thermal conductivity is a crucial parameter in the quest for high figures of merit in thermoelectric devices.

Also includes the following papers; A Model For Lattice Thermal Conductivity at Low Temperatures, by Joseph Callaway (Sci. Paper 431FD280-P1); An Empirical Correlation for High Temperature Lattice Thermal Conductivity, by R. W. Keyes; Considerations Relating to Peltier Cooling at 77°K, by R. W. Keyes (Res. Memo 6-94416-3-M8); and Correlations Between Mobility and Effective Mass in Semiconductors, by R. W. Keyes (Sci. Paper 9-1038-P47).

138. Westinghouse Research Laboratories, Pittsburgh, Pa. **Thermoelectricity.** Final Report. $\frac{3}{4}$ in. thick, Jan. 1, 1959. (Prog. Rpt. 12) (Contract Nobs-72361).

Limited availability.

See also entries for Cornish, A. J., Faust, J. W., Jr., and items 986, 987, 988.

139. Westinghouse Research Laboratories, Pittsburgh, Pa. **Thermoelectricity quarterly.** 1 in. thick, May 11, 1959. (Prog. Rept. 2) (Contract Nobs-77043) (AD-216 781).

The present report describes a number of experiments directed at determining vapor pressures of thermoelectric materials. In order that the thermoelectric parameters of all materials studied should be readily available in a single reference, this report and all succeeding reports will contain a complete set of data. These data are found in Part B.

Also included are Scientific Paper 431-FD-410-P3, Computation of Efficiency of Thermoelectric Devices, by B. Sherman, R. R. Heikes, and R. W. Ure, Jr.; and Research Memo 431-FD-410-M1, Radiative Heat Transfer in Thermoelectric Materials, by T. Holstein.

140. Westinghouse Research Laboratories, Pittsburgh, Pa. **Thermoelectricity quarterly.** $1\frac{1}{4}$ in. thick. Aug. 13, 1959. (Prog. Rept. 3) (Contract Nobs-77043).

The work of this quarter has pointed to several materials which have very definite possibilities for use in the temperature range from 1000°K to 1500°K. Two of these are to be found among the rare earth sulfides, a group of materials not previously investigated to any great extent.

141. Wetch, J. R. **Nuclear Reactors as auxiliary power sources.** *Air Univ. Quart. Rev.* **11**: 146–156, Fall and Winter 1959.

It is indicated that power conversion systems based upon the thermoelectric or thermionic principles are very attractive for space flight.

142. Wright, D. A. **Compound semiconductors,** *Electron. Eng.* **31**: 659–665, Nov. 1959.

The parameters which are important for thermoelectric applications are mentioned briefly.

143. Wright, D. A. **Thermoelectric cooling.** *In* Progress in Cryogenics, vl. 1, ed. by K. Mendelssohn, p. 33–61, New York, Academic Press, 1959.

Considers the choice of a material for thermoelectric refrigeration.

144. Wright, D. A. **Thermoelectric effects.** *In* NSIA-ARDC Conference on Molecular Electronics, November 13–14, 1958, Washington, D.C., p. 42–46, Washington, D.C. National Security Industrial Association, 1959.

Discusses thermoelectric performance of semiconductors in terms of the figure of merit which serves as a criterion for both refrigeration and generation; then reviews General Electric Co., work with bismuth telluride and other materials. Variation of thermoelectric properties with temperature; performance at present attainable and future developments are also mentioned.

145. White, W. C. **Some experiments with Peltier effect.** *Elec. Eng.* **70**: 589–591, Jly, 1951.

The possibility of using Peltier effect in a thermoelectric power generator. A couple of Bi–Sb and a Bi–Sn alloy was used with a cooling effect of 10°C. Efficiency was low. Conclusion was that there was no chance of developing any sort of generator or refrigerator.

146. Wilson, G. W. and Lindley, B. C. **Thermoelectric power. An investigation of its possibilities.** Parts I, II, III. *Eng.* **188**: 97–99, Aug. 28, 129–132, figs., Sept. 4; 161–162, Sept. 11, 1959.

147. Winkler, V. **Characteristic data of a non-degenerate self-semiconductor from electrical measurements.** *Helv. Phys. Acta.* **27**: 192–193, 1954.

In German.

With appropriate theoretical assumptions, semiconductors can be characterised by measurements of the Hall effect, thermal conductivity, and differential thermo-potential.

148. Zener, Clarence. **New Ceramics convert heat to electricity.** *Iron Age.* **182**: 125, Sept. 11, 1958.

Quotes statement of Dr. Clarence Zener, director of Westinghouse research regarding practical applications of recently announced new thermoelectric materials.

149. Zener, Clarence. **Thermoelectricity. Its impact upon science and technology.** *Indus. Sci. & Eng.* **5**: 26–30, figs., Oct. 1958.

A general article giving background information, reasons for resurgence of interest in thermoelectricity and possible future applications.

150. ZENER, CLARENCE. **Thermoelectric conversion.** *In* Electro-Optical Systems, Inc. Proceedings of a Seminar on Advanced Energy Sources and Conversion Techniques, Pasadena, California, 3–7 November, 1958, vol. 1, p. 95–98, figs., Pasadena, Calif., 1958. (Contract DA-36-039 SC 78064) (AD 209301) (PB 151461).

Answers two questions—how efficient will thermoelectric power generators become, and what will be the weight per kW capacity of these generators?

151. ABELES, F. **Resistivity and thermoelectric power of metals containing grain boundaries.** *J. Phys. et Radium* **16**: 345–355, Jly. 1955.

In French.

Estimates of the resistance and thermoelectric power increase in metals due to the plastic deformation which occurs at grain boundaries, and of the analogous problem of the resistivity and thermoelectric power of alloys of monovalent metals.

152. **Annual review of physical chemistry,** v. 10, ed. by H. EYRING, C. J. CHRISTENSEN and H. S. JOHNSTON. 537 p., Palo Alto, Calif. Annual Reviews, Inc., 1959.

Thermoelectric power is briefly mentioned, p.412.

153. ATTERTON, D. V. and HOUSEMAN, D. H. **The intermediate metal thermocouple in metal/mould interface temperature measurements.** *Brit. Foundryman.* **51**: 77–82, Feb. 1958.

The development of a method of using the molten metal to form the junction between dissimilar metals is described and 280-lb steel castings were examined by the technique. Calibration showed errors due to contamination to be negligible and initial freezing and subsequent remelting of the metal initially entering the mould was demonstrated. Comparisons with sheathed couples were made.

154. AUBERTIN, F. and CRUSSARD, C. **Thermoelectric force. Accurate methods of applications to the study of heterogeneity of alloys structures.** *Met. Ital.* **44**: 548–549, Nov. 1952.

In French.

Describes methods and gives data obtained on Al alloys and mild steels. Data are tabulated and charted.

155. AVAK'YANTS, G. M. **On the theory of equations of transfer in strong electric fields. I.** *Zhurn. Eksp. i Teor. Fiz.* **26**: 562–575, 1954.

In Russian. Trans. no. 59–18679 available from SLA or LC.

The transfer of heat and electricity in semiconductors is investigated for the conditions when electron ("hole") gas of the semiconductor is considerably heated in an electric field, associated with the passing of current through the semiconductor. Since basic equations and the formula derived therefrom for thermoelectric and galvanomagnetic effects are omitted from the present translation, access to the Russian text is necessary. (Tech. Trans. **2**: 828, Dec. 4, 1959).

156. AVAK'YANTS, G. M. **On the theory of equations of transfer in strong electric fields. II.** *Zhurn. Eksp. i Teor. Fiz.* **26**: 668–679, 1954.

Trans. no. 59-18680 available from SLA or LC.

The coefficients in formulas (which are omitted in the translation) describing phenomena of heat and electricity transfer in semiconductors in the case of intensive heating of electron (hole) gas are shown to be functions of current density j and charge carriers concentration N. All coefficients are shown to be even functions of j, and only three powers of current are met with: j^0, j^2, and j^4. They are also shown to be even functions relative to N if we ignore the dependence of N in terms containing expressions of the type $(j/jT)\,(x^v, 1nN)$. With this only three powers of concentration are met with; N^0, N^1, and N^4. The power of the current j or concentration N, occurring in formulas for the coefficients listed above, does not depend on the power of the impulse n in the formula for the dependence of the length of free path on impulse: $1+1_np^n$. (Tech. Trans. **2**: 828, Dec. 4, 1959).

157. AZBEL', M. I., KAGANOV, M. I. and LIFSHITS, I. M. **Thermal conductivity and thermoelectric phenomena in metals in a magnetic field.** *Zhurn. Eksp. u. Teor. Fiz.* **32**: 1188–1192, 1957.

In Russian. Translation in Soviet Phys. JETP. **5**: 967–970, 1957.

Asymptotic expressions for the tensors of the thermal conductivity and Thomson coefficients in a strong magnetic field were found. No special assumptions regarding the dispersion law or the collision integral were made in the deduction.

158. AZUMA, K. and KAMETANI, H. **Generation of emf during melting and freezing of ionic crystalline substances.** *Phys. Soc. Japan. J.* **12**: 313–314, Mar. 1957.

The apparatus used in the studies is illustrated and the methodology described. Maximum emf obtained for KCl and similar substances are listed.

159. BALDER, T. C. **Influence of the Peltier effect in resistance welding.** *Philips Tech. Rev.* **20**: 188–192, Feb. 1959.

Examines the connection between Peltier heat and the behaviour of a thermocouple made from contacting metals in order to be in a position to predict whether in a given case the Peltier effect may be expected to influence a weld significantly or not.

160. BERGERON, C. J., JR., GRENIER, C. G. and REYNOLDS, J. M. **Oscillations in the Ettingshausen-Nernst and thermoelectric effects in zinc at low temperatures.** *Am. Phys. Soc. Bull.* **4**: 5–6, Jan. 28, 1959.

Abstract of paper.

"Measurements in a zinc single crystal of the Ettingshausen-Nernst effect and the thermoelectric effect show de Haas van Alphen type oscillations. The period of these oscillations in 1/H is the same as that of the Hall effect and magnetoresistance. Since neither of these effects possess a monotonic component they lend themselves very easily to harmonic analysis."—Entire item quoted.

161. BERGERON, C. J., JR. **Thermo- and galvanomagnetic potentials in a single crystal of zinc at liquid helium temperatures.** PhD Thesis, Louisiana State University, 1959.

"All experiments were performed with a constant electrical or heat current; the magnetic field varied at a constant rate from 1 to 11 K. G. The transverse and longitudinal (parallel to the current components of the p tensor were the galvanomagnetic quantities studied. These are associated with the Hall effect and magnetoresistance respectively. In the thermal case, the measured effects were the thermoelectric voltage and the transverse Ettingshausen-Nernst potential for a constant heat current. Oscillations as a function of magnetic field strength were observed in all of these potentials. The measured period for the transverse oscillations as a function of 1/H was $6{\cdot}2 \times 1{\cdot}0^{-5}$ gauss$^{-1} \pm 0{\cdot}5\%$. Both transverse effects possessed strong second harmonic oscillations. The oscillations in the longitudinal effects both exhibited a phase inversion in the neighbourhood of 4·2 K.G., the same field region for which the gross Hall field changed sign from a plus to a minus value. In this same field region the period of the oscillations for the longitudinal effects was half that of its low and high field values, i.e., the period of the second harmonic. If we modify Zil'berman's theory by inserting Grimsal's and Levinger's expression for an oscillatory number of effective carriers into Zil'berman's solution of the electrical conductivity tensor, we can offer some empirical correlations between the reversal of sign of the Hall effect and: (1) the phase reversal of the magnetoresistance oscillations, (2) the strong second harmonic content of these oscillations in the region of the phase reversal, and (3) the quadratic shape of the envelope to the magnetoresistance oscillations in this region.

Zil'berman's theory implicitly assumes the Weidemann–Franz law. However, Azbel *et al.* has shown that for the strong magnetic fields and low temperatures for which Zil'berman's theory applies the Weidemann-Franz law is indeed valid. If we assume that the difference of the absolute thermoelectric power and the temperature derivative of the chemical potential is negligible we arrive at an empirical explanation of the phase reversal of the oscillations in the longitudinal thermal potential and the presence of the large second harmonic in the neighbourhood of the phase reversal." *Dissertation Abs.* **20**: 1054, 1959.

162. BERMAN, R. **Some experiments on thermal contact at low temperatures.** *J. Appl. Phys.* **27**: 318–323, Apr. 1956.

An apparatus for studying heat contact at low temperatures is described. Measurements of heat transfer between various surfaces in vacuo have been made. The thermal conductance is indepdent of the area of the surfaces and is nearly proportional to the force between them, up to forces of about 200 lb. At helium temperatures the conductance between all types of surfaces examined in proportional to T^2, but the temperature dependence is small at nitrogen temperatures. For metal contacts the electrical conductance is extremely sensitive to the previous history of the surfaces, but the heat conductance is little dependent on this. The thermal conductance is always much greater than corresponds to the electrical conductance according to the Wiedemann–Franz–Lorenz law and this fact, together with the differing behaviour of the two conductances under charging loads, suggests that nearly all the heat flow takes place through electrically non-conducting parts of the surface. The main results are collected together in a table.

163. BESKROVNYI, A. K. **The thermoelectric nonuniformity of aluminium during plastic deformation.** *Khar'kov. Politekh. Inst. Trudy.* **9**: 155–156, 1957.

In Russian.

"Thermoelectric non-uniformity during the plastic deformation of Al was studied and the thermoelectric characteristics measured at various degrees of deformation (D). It was shown that resulting from plastic D there are areas which possess equivalent properties to the original metal. Arising from the fact that the escape energy of electrons from extended metal is less, but from compressed metal more, it is concluded that when Al is deformed plastically, there are areas of both extension and compression. As the degree of D increases, the number of areas with different contact potentials increases. It is suggested that the areas of compressed material, which are energetically more stable than the extended areas, form recrystallization centres for the formation of new grains." *Abs. J. Metall. Nors.* 10, 11, **12**: 193, 1957.

164. BIERWIRTH, G. **Thermoelektrische bestimmung des siliziums in gusseisen. (Thermoelectric analysis of silicon in cast iron).** *Giesserei* **45**: 546–549, Sept. 11, 1958.

In German.

Experimental results are reported and literature is quoted, to demonstrate that, if only certain experimental conditions are maintained, the gravimetric determination of Si in cast iron can be replaced by a thermoelectric method. Time is saved; no chemicals are required; a degree of accuracy of $\pm 0{\cdot}04\%$ Si is achieved.

165. BLUE, M. D. **Thermoelectric effects in copper-gold alloys.** *Phys. Rev.* **117**: 134–138, figs., Jan. 1, 1960.

Measurements of the resistivity and thermoelectric power of the binary alloy CuAu and of CuAu alloys containing dilute amounts of Ni are analyzed using the thermoelectric power formula of Mott. At the transition temperature, anomalies in the thermoelectric power are observed. The scattering cross section and its derivative with respect to energy for Ni in CuAu are determined. The results are similar in value to these same

parameters measured for dilute amounts of Ni in Cu.

166. BORELIUS, G., KEESOM, W. H. and JOHANSSON, C. H. **Measurement of the thermoelectric Thomson effect at the temperatures of liquid hydrogen.** *Ned. Akad. Wetens. Proc.* **31**: 1046–1058, 1928.

In English.

"Measurements down to 20° abs. were made on 2 wires, Cu and Ag alloyed with a little Au, and down to 70° on pure Cu wire. The method was largely that of Borelius (*Ann-Physk* **65**: 520, 1921), the ends of the wire being at constant temperature, and the temperature of the centre being varied by means of an electric current through it.

167. BORISOV, B. I. **Temperatura i vibratsii pri rezanii metallov. (Temperature and vibrations in metal machining).** *Vest. Mashinostroenya* **37**: 40–42, Sept. 1957.

In Russian.

Describes a simple thermoelectric method for investigation of vibrations originating during metal machining, and derives a relation between temperature of tool cutting edge and vibration. Using this formula, the vibration can be calculated on the basis of temperature changes and vice versa. Changes of thermoelectric power at various conditions of vibration are recorded by means of a magnetoelectric oscillograph.

168. BOUCHARD, J. **Effect of reversible and irreversible changes of magnetization on the thermoelectric power of ferromagnetics.** *Acad. Sci. Paris. Compt. Rend.* **226**: 1895–1897, June 1948.

In French.

Discusses variation of the thermoelectric power $\triangle E$ between magnetized and unmagnetized specimens of a ferromagnetic, for a fixed temperature difference as a function of H. Correspondence between $\triangle E$ loops and hysteresis loops is noted and attention is drawn to distinction between variations of $\triangle E$ occurring in irreversible and reversible regions of magnetization. Effects of tension are also reported.

169. BOUCHARD, J. **Influence of magnetization on the thermoelectric power of magnetic materials.** *Acad. Sci. Paris. Compt. Rend.* **226**: 1708–1710, May 24, 1948.

In French.

Measurements of the thermoelectric power of a couple composed of a Cu wire and a wire of steel or Ni alloy were made at different temperatures, and showed a discontinuity at the Curie point. Similar measurements were also made on a couple containing two wires of the same material, one magnetized, the other not.

170. BRIDGMAN, P. W. **General survey of certain results in the field of high pressure physics.** *Wash. Acad. Sci. J.* **38**: 145–156, May 15, 1948.

Nobel Laureate Lecture. Improvements in experimental technique are described. Compressibilities and polymorphic transitions of some thirty elements and simple compounds have been studied with pressures up to 100,000 kg/cm^2. A few thermal conductivity measurements have shown no change in the Weidemann-Franz ratio with high pressure. The effects of high pressure on the thermoelectric effects are sometimes complicated.

171. BRIDGMAN, P. W. **The physics of high pressure.** 398 p., figs., London, Bell, 1931.

Ch. X, Effect of pressure on thermoelectric properties.

172. BRIDGMAN, P. W. **The transverse thermoelectric effect in metal crystals.** *Natl. Acsd. Sci. Proc.* **13**: 46–50, Jan. 1927.

Reports the finding of the transverse Peltier effect in bismuth, zinc, tin and cadmium.

173. BRINDLEY, G. W. **A thermoelectric study of the cold-rolling and heat-treatment of copper.** *In* Report of a Conference on Strength of Solids, p. 95–104, London, The Physical Society, 1948.

Discussion p. 105–106.

Data are given for the thermo-emf, E, of cold-rolled and heat-treated copper strips relative to a standard annealed strip for a wide range of rolling reductions and annealing temperatures.

174. BRINDLEY, G. W. **A thermo-electric study of the cold-working and annealing of copper.** *Leeds Phil. and Lit. Soc. Proc.* **4**: 1–12, Jly. 1941.

This paper is concerned with two aspects of the thermal emf, produced in metals by cold-working. (1) the variation of thermal emf, with degree of cold-working; (2) the use of the thermal emf as an indicator of the state of a metal when cold-worked and then subjected to heat treatment. The experiments are confined to cold-rolled copper.

175. BROOM, T. and HAM, R. K. **The effects of lattice defects on some physical properties in metals.** *In* Vacancies and Other Point Defects in Metals and Alloys, p. 41–78, Inst. of Metals, London, 1958.

Theoretical and experimental work on the effects of lattice defects on stored energy, electrical resistivity, density, X-ray lattice parameters, thermoelectric properties, thermal conductivity, magnetic properties and nuclear magnetic resonance.

176. BYCHKOV, I. A., GUREVICH, L. E. and NEDLIN, G. M. **Thermoelectric phenomena in strong magnetic fields in metals possessing various fermi surfaces.** *Zhurn. Eksp. i Teor. Fiz.* **37**: 534–539, Aug. 1959.

In Russian. Trans. in *Soviet Phys. JETP* **37**: 377–380, Feb. 1960.

The asymptotic behaviour of the thermoelectric force. Peltier coefficients and Thomson coefficients for metals with closed Fermi surfaces and open surfaces of the "corrugated cylinder" and "space net" type is investigated on the basis of the quasi-classical theory of kinetic phenomena in metals located in strong magnetic fields as developed by

Lifshitz, Azbel, and Kaganov and Lifshitz and Peschansky. (BTR **9**: 53a, Jan. 1960).

177. California University. Radiation Laboratory, Livermore, Calif. **Use of thermal electromotive forces to produce magnetic field in a controlled thermonuclear reactor,** by T. G. NORTHROP. 15 p., Dec. 1954. (Rpt. 4427). (Contract W. 7405–eng–48).

The possible use of thermal emf's to produce the plasma-containing magnetic field in a thermonuclear reactor is investigated. In any such machine the magnet producing the containing field will have to be protected from the neutron flux by a substance such as lithium with a high neutron capture cross section. This metal could be cooled by circulation through the hot junctions of a thermopile. A machine in which all of the necessary field is supplied by the kinetic energy of the neutrons from the D-D reactions appears to be large because most of the power is lost to the cold junctions by thermal conduction. Only 5 to 10% of it is accounted for by magnet dissipation. Two cases have been worked out: the cylindrical machine with minimum possible magnet volume and the machine with minimum outer diameter.

178. CHANU, JACQUES. **Thermodiffusion potentials in electrolytes. Initial Thermodiffusion potentials.** *J. Chim. Phys.* **51**: 390–398, Jly./Aug. 1954.

In French.

An analysis based on analogy with thermoelectricity in metals has been made, to derive an expression for the potential difference between two electrodes immersed in hot and cold parts of a solution of a univalent electrolyte without convection, and when Soret equilibrium is established. Measurements with Ag/AgCl half-cells in NaCl and KCl have revealed an almost strictly linear variation of $\triangle\Phi$ with $\triangle T$($\triangle\Phi$=p.d.); $\triangle\Phi/\triangle T$ decreases slightly when the concentration increases, indicating that the mean ion transfer entropy is negative. Individual ion transfer entropies cannot be calculated from such measurements.

179. CHOU, YUAN-HSI. **Thermodynamics of liquid blast-furnace slags.** *Freiberger Forschung* **15B**: 18–47, 1957.

Not examined.

"From existing thermal and emf values, the activities of CaO and SiO_2 in liquid slags of CaO–SiO_2 and CaO-SiO_2–Al_2O_3 at 1600_3 were calculated with pure solid CaO or β-crystobalite as standards. From the available thermal data and distribution values, the activity coefficient of MnO in blast-furnace slags was calculated for the temperatures 1400°, 1500°, and 1600° with pure solid MnO as the standard." *Chem. Abs.* **51**: 12783, 1957.

180. CONWELL, E. M. **Impurity band conduction in germanium and silicon.** *Phys. Rev.* **103**: 51–61, Jly. 1, 1956.

Paper attempts to establish idea of impurity band conduction on a firmer theoretical basis for Ge and Si. The question of the sign of the carriers in the impurity band is discussed, and it is shown that the sign reversal of thermoelectric power observed for the impurity band need not imply a change in sign of the effective mass.

181. CRUSSARD, C. and AUBERTIN, F. **Effect of deformation on the thermoelectric power of metals.** *Acad. Sci. Paris. Compt. Rend.* **226**: 75–76, Jan. 5, 1948.

In French.

Measurements were made for Cu, Al, Fe and Ni for elastic and plastic deformations. The results show that the effect is much greater for the ferromagnetic metals than for Cu and Al.

182. CRUSSARD, C. **Thermoelectric properties of metals—influence of cold work and impurities.** *In* Report of a Conference on Strength of Solids, p. 119–133, London, The Physical Society, 1948.

"The plastic effect has been extensively studied for non-magnetic metals; it consists in an increase of the thermoelectric power. A detailed experimental survey of the different possible causes has been made, leading to the conclusion that only highly localized structure imperfections or internal stresses (probably dislocations) are involved in the phenomena. A general survey of the actions of impurities dissolved in a metal on its thermoelectric power has been made, and an empirical law found. These studies show that thermoelectric power offers a very sensitive means of detecting the state (dissolved or precipitated) of minute amounts of foreign atoms. Some applications are given."

(Last two paragraphs of article quoted.)

183. DAHL, O. and STARKE, E. **Reordering processes in copper alloys on the basis of thermoelectric power measurements.** *Z. Metallk.* **50**: 410–412, Jly. 1959.

In German.

Temperature dependence of the thermoelectric power of various Cu–Ni–Zn, Cu–Ni and Cu–Zn alloys and of Cu_3Au. Results are interpreted in terms of ordering processes.

184. DAVIDSON, P. M. **The theory of the Thomson effect in electrical contacts.** *Inst. Elec. Engrs. Proc.* 96 (*Pt.* 1): 293–295, Nov. 1949.

A general theorem is given concerning the influence of the Thomson effect on the location of the maximum temperature in an electrical contact. Its application to the theory of fine transfer in electrical contacts is discussed.

185. DAVIS, G. E. **A method of measuring high intensities at the focus of a parabolic reflector with large relative aperture.** *Opt. Soc. Am. J.* **39**: 541–543, Jly. 1949.

A receiving cell with special stops is used to determine the energy distribution thermoelectrically. The sources of error with two different types of aperture are discussed. Errors due to heat radiated from the stop are minimized by using short exposures and by substituting a reflector for the stop immediately after the exposure. A suitable

amount and an adjusting mechanism for the cell are described.

186. DIETRICH, I. **Benedicks effect in fine-crystalline metal wires.** *Z. Physik.* **129**: 440–448, 1951.

In German.

Considers whether a monometallic fine-crystalline wire should show a Benedicks effect (thermoelectric potential difference between two points at the same temperature but with an asymmetric temperature distribution in the region between them). Theory and experiment (described in detail) show that the effect, if present, is very small.

187. DIETRICH, I. **Peltier effect in monometallic contacts.** *Z. Angew. Phys.* **2**: 128–131, 1950.

In German.

It was found that an effect analogous to the Peltier effect is observable in a monometallic contact, provided an impurity film is present. The effect disappears at high temperatures. Theory and experimental data are given.

188. DIETRICH, I. and RUCHARDT, E. **Therma potentials in platinum contacts.** *Z. Naturforsch.* **4a**: 482–486, Oct. 1949.

In German.

It is shown experimentally that the thermal potential observed when crossed Pt wires are unsymmetrically heated is due to a thin film of impurity between them. The thermal potential, and the thermal resistance of the unimolecular impurity film, were determined. The measurements were in good agreement with values calculated from the theory of Kohler. See *Ann. Phys.* **38**: 542, 1940 and *Naturwissenschaften* **29**: 164, 1941.

189. DRUYVESTEYN, M. J. and VAN OOIJEN, D. J. **Change of absolute thermoelectric power and electrical resistivity of copper by cold-working at liquid air and room temperature.** *Appl. Sci. Res.* **5B**: 437–441, 1956.

Studies of 250 micron diameter wires; some were vacuum annealed at 550°C, cold worked by rolling at room temperature; others rolled in liquid air; subsequently both were annealed at 90°C; thermoelectric force of deformed wires against undeformed wires against undeformed specimen measured as function of hot junction temperature, with cold junction in liquid air.

190. DUGDALE, J. S. and MACDONALD, D. K. C. **Lattice thermal conductivity.** *Phys. Rev.* **98**: 1751–1752, June 15, 1955.

Consideration of the anharmonic properties of a linear chain suggests that the dimensionless quantity $\alpha\gamma T$ is in general a measure of the anharmonicity of a lattice (α is the thermal expansion coefficient and γ the Grüneisen parameter). It is therefore proposed that the mean free path for lattice vibrations in an insulator should, in the classical temperature region, be approximately $A_0/\alpha\gamma T$, where A_0 is the lattice spacing. Reasonably good agreement with experiment is found.

191. EWLES, J. and BARMBY, D. S. **Optical and electrical properties of some oxygen activated alkali halides.** *Phys. Soc. Proc.* **69B**: 670–678, June 1956.

Phosphors showing well-resolved bands in their emission spectra have been made by thermal treatment of alkali halides in the presence of oxygen. The emission spectra are strikingly similar with quite different halides all showing a wave number difference of about 1000 cm^{-1} between the peaks of the main components of the band system. The chlorides and bromides show abnormal thermoelectric effects. It is suggested that both the similarity in the emission spectra and the abnormal thermoelectric effects can be accounted for by the absorption of O_2^+ on active sites.

192. FRAPPE, GERALD and LEPOUTRE, GERALD. **The thermoelectric effect in electrolytic solutions. III. Solutions of potassium in liquid ammonia compared with the fermi-dirac electron gas.** *J. Chim. Phys.* **54**: 242–245, 1957.

In French.

The thermodynamic functions of the Fermi-Dirac electron gas as a function of concentration are calculated. A plot of the experimental thermoelectric coefficients vs. concentration agrees well with the plot of entropy vs. concentration calcuated for the Fermi-Dirac electron gas.

193. FUNATOGAWA, Z. **The change in thermal emf produced by magnetization of a single crystal of iron.** *Phys. Soc. Japan J.* **5**: 311–316, Sept./Oct. 1950.

Measurements were made of the thermoelectric power of Fe single crystals against Cu as the magnetization increases from remanence to saturation. A correspondence between magnetostriction and magneto-thermoelectricity was established.

194. FUNATOGAWA, Z. **On the magneto-thermoelectric power of iron crystal at high temperature.** *Phys. Soc. Japan J.* **6**: 256–260, Jly./Aug. 1951.

Previous experiments on the magnetization dependence of the thermoelectric power were extended to higher temperature. It was found that E_{100} (the change between remanence and saturation along the [100] direction) decreases almost linearly with increasing temperature, while E_{111} remains constant up to about 200°C and then decreases, both tending to zero at the Curie point. The relation with the temperature variation of the magnetostriction coefficient is shown.

195. GALT, J. K. **Note on the effect of impurities and cold work on the thermoelectric power of aluminium.** *Phil. Mag.* **40**: 309–314, Mar. 1949.

Recent observations on the thermoelectric power of impure Al are discussed theoretically. Dissolved impurities produce a change in the thermoelectric power of pure Al which can be understood in terms of the electronic band structure of Al. When the impure Al is cold worked, the variation of its power with time and temperature

is changed. An explanation of this in terms of the theory of dislocations is proposed.

196. GAYLORD, E. W., HUGHES, W. F., APPL, F. C. and LING, F. F. **On the theoretical analysis of a dynamic thermocouple.** *Am. Soc. Mech. Engrs. Trans.* **80**: 307–310, 1958.

The dynamic thermocouple in which one junction is formed by the rubbing together of two dissimilar metals is analyzed theoretically. It is shown that, in the case of semi-infinite rubbing solids with many randomly distributed contacts, small in area compared with the distance between them, the potential measured by thermocouple lead placed at an infinite distance away from the contact areas is the average of the Seebeck emf, corresponding to the contact temperature weighted by the square root of the areas.

197. GEBALLE, T. H. **Radiation effects in semiconductors: thermal conductivity and thermoelectric power.** *J. Appl. Phys.* **30**: 1153–1157, figs., Aug. 1959.

The use of thermal conduction and thermoelectric measurements in studying radiation damage effects in semiconductors is discussed. The conclusion is reached that in the present state of knowledge such measurements will probably be more helpful in studying the kinetics of the formation and annealing of radiation-introduced defects than in characterizing the structure of such defects.

198. GELDMACHER, R. C. **On electrothermomechanical transients in cylindrical conductors subjected to axial electric fields.** *Dissertation Abs.* **20**: 3678, 1960.

Abstract of Ph.D. dissertation, Northwestern University, 1959.

Thermoelectric and electromagnetic effects were considered relative to their influence on the distribution of temperature and electric field within the conductor.

199. GINZBURG, V. L. **Thermoelectric phenomena in superconductors.** *Zhurn. Eksp. i Teor. Fiz.* **14**: 177–183, 1944.

In Russian. Trans. in Soviet Phys. JETP **8**: 148–153, 1944.

Theoretical. Superconductors with normal temperature gradients should show a normal current, i^N. In isotropic conductors this is counteracted by a super-conducting current i^n. In superconducting crystals the thermal current should be detectable by the magnetic field produced.

200. GOLDRING, D. A. **Determination of the thickness of plating by measuring the thermal emf.** *Instr. Construction* p. 26–27, Jan. 1959.

A thermoelectric method for the measurement of plating thickness (*e.g.*, nickel on steel) is described.

201. GOMBAY, L., GYULAI, J. and LANG, J. **Ueber die bestimmung der konzentration und der beweglichkeit der ladungstraeger in gemischten halbleitern. (Determination of the concentration and the mobility of carriers in mixed semiconductors).** *Acta Phys. Acad. Sci. Hung.* **8**: 203–209, 1957.

In German.

A new method of determining the concentration and mobility of electrons by measuring the light conductivity, the Hall constant, the thermoelectric force, and the resistivity change occurring in a transverse magnetic field.

202. GORE, G. **Some relations of heat to voltaic and thermoelectric action of metals in electrolytes.** *Roy. Soc. London. Proc.* **37**: 251–291, 1884.

An experiment is described in which the objective was to ascertain the thermoelectric actions of a series of metals in particular liquids; and to examine the relations of the thermoelectric to the chemicoelectric behaviour of metals in electrolytes, and to ordinary chemical corrosion, and the source of voltaic currents.

203. GRANVILLE, J. W. and HOGARTH, C. A. **A study of thermoelectric effects at the surfaces of transistor materials.** *Phys. Soc. Proc.* **64**: 488–494, June 1, 1951.

The surfaces of various specimens of Ge and PbS have been explored with a whisker contact, and the character of the conduction mechanism in relatively small regions has been examined by the polarity of (a) the photo-voltaic effect, (b) the rectification, and (c) the thermoelectric effect. Methods (a) and (b) give results characteristic of the bulk material as determined by Hall effect measurement whereas method (c) only gives results consistent with (a) and (b) for uncontaminated cleaved surfaces or for surfaces which have been etched after polishing. For polished surfaces, anomalous effects are obtained and point to the existence of a layer on the surface of character different from that of the bulk semiconductor.

204. GROSS, B. **Theory of the thermodielectric effect.** *Acad. Brasil Sci. Ann.* **25**: 175–196, 1953.

Not examined.

"An extended analysis of the electrical phenomena at the melting or freezing interface of an ionic compound when the transition probabilities of the positive and negative ions through the boundary layer are unequal. The electrical conductivity of the solid phase is assumed negligibly small, so that during freezing a quasi-permanent space-charge is built into the solid. The boundary layer forms an electrical double layer. Expressions are obtained for the open-circuit potential (with zero initial bias) for a uniform rate of freezing, and for the short-circuit current when the freezing is suddenly held up, and the currents during freezing and melting are discussed." *Sci. Abs.* **57A**: 2410, 1954.

205. GRUNEISEN, E. **Ueber die bestimmung des metallischen waermeleitvermoegens und ueber sein verhaltnis zur elektrischen leitfahigkeit. (The determination of thermo-conductive capabilities of metals and their relation to electrical conductivity).** *Ann. Physik.* **308**: 43–47, 1900.

In German.

206. GUREVICH, L. E. and NEDLIN, G. M. **Thermoelectric coefficients of metals in strong magnetic fields and the effect of drag of electrons by phonons.** *Soviet Phys. JETP* **37**: 546–552, Mar. 1960.

Translation of *Zhurn Eksp. i. Teor. Fiz.* **37**: 765–776, Sept. 1959.

The behaviour of the thermoelectric tensor in strong magnetic fields when the electron Larmor frequency is greater than the collision frequency is considered by the methods proposed by Lifshitz, Abel, and Kaganov. Drag of electrons by phonons is taken into account and it is shown that this effect significantly changes the asymptotic values of the tensor (for large field values) as well as its dependence on the direction of the magnetic field relative to the crystal axes (in the case of a complex topology of the Fermi surface).

207. HEHENKAMP, THEODOR. **Investigation of Thermoelectric wear of hard metal turning tools and its elimination by electrical compensation.** *Arch. Eisenhüttw.* **29**: 249–256, Apr. 1958.

In German.

Thermoelectric currents resulting from contact at different temperatures between tool and production part cause wear by transfer of matter.

208. HEISENBERG, W. **Thermodynamic consideration about the problem of superconductivity.** *Ann. Physik.* **3**: 289–296, 1948.

In German.

From the empirical behaviour of the specific heat certain conclusions are drawn about the electronic condensation phenomenon assumed to occur in the superconducting transition. The thermoelectric effects are discussed and the electric field calculated which must occur in the presence of a temperature gradient. The behaviour of a rotating superconductor is discussed in connection with the thermodynamics of the Meissner effect.

209. HILL, R. A. W. **Thermal measurements on small transient systems.** *Nature* **170**: 29–30, Jly. 5, 1952.

It has been found possible to heat the wires of a thermocouple by the passage of a current and at the same time to record the temperature of the junction by its thermo-emf, the concomitant voltage being separated from the thermo-emf by using h.f. current and inductance-capacitance filters. The thermal constants of poor conductors can be measured. Apparatus as small as 1 cm. long by 0·1 cm dia. can be used, and the speed of measurement, ~ 100 m/sec., enables measurements at high temperatures and under transient conditions to be made.

210. HOGARTH, C. A. **Variation of thermoelectric power of electronic semiconductors with vapor pressure.** *Nature* **161**: 60–61, Jan. 10, 1948.

The principle of mass action is applied to determine the effect of varying the vapour pressure of one of the constituents of the substance. The resulting formula $dE/dT = -Cr \log Pv \pm$ const. is shown to yield values of Cr in close agreement with experimental values derived from Cu_2O, NiO and ZnO.

211. HOGARTH, C. A. and ANDREWS, J. P. **Variation with oxygen pressure of the thermoelectric power of aluminium.** *Phil. Mag.* **40**: 273–282, Mar. 1949.

Experiments are described which show that (a) over the temperature range 240–570°C, the thermoelectric power of a CdO/Pt couple varies with the absolute temperature T, according to the equation $dE/dT = -a + b/T$, the pressure of the O in the surrounding atmosphere remaining constant; and (b) at constant temperature the power is a linear function of the log of the O pressure. Simple theory predicts this form of variation but not the correct values of constants. The quantity b varies smoothly with the O pressure.

212. HÖRIG, HEINRICH. **Ueber den einfluss des druckes auf die thermoelektrische stellung des quecksilbers und der eutektischen kalium-natrium-legierung. (The effect of pressure on the thermoelectric position of mercury and of the eutectic potassium-sodium alloy).** *Ann. Physik.* **28**: 371–412, figs., 1909.

In German.

Concerns an investigation of liquid mercury and NaK eutectic to 1400 kg./cm² and 150°. Effect of pressure on both substances was found to be linear, and practically the same on both, $2{\cdot}37$ and $2{\cdot}32 + 10^{-10}$, respectively.

213. IOFFE, A. F. **Thermal conduction in semiconductors.** *Nuovo Cimento* 3 (*Suppl.* 4): 702–715, 1956.

The theory that the thermal conductivity is the sum of the conductivity caused by electrons and that caused by phonons, and that the electron part is directly related to electrical conductivity holds approximately for extrinsic conduction only. At greater values of free charge the scattering of phonons by the current carriers may occur. Additional conductivity is caused by the diffusional flow of electron-hole pairs, excition flow, the drag of phonons by pair flow, by exciton flow, and heat transfer caused by radiation.

214. IOFFE, A. F. **Thermal conductivity of semiconductors.** *Akad. Nauk. SSSR. Izvest.* **20**: 65–75, 1956.

In Russian. Trans. No. R–943 available from Special Libraries Association Translation Center, Crerar Library, Chicago.

Two mechanisms of thermal conductivity exist in semiconductors, one of heatwave character and an electronic mechanism; the latter is directly related to electrical conductivity and differs according to whether the lattice electrons are in the non-degenerate or degenerate state. The electronic mechanism is strongly influenced by the flow of, and the consequent capture of phonons by electron-hole pairs and excitons and by radiant energy transfer. Best suited for thermocouples is substance

with highest ratio of electron mobility to thermal conductivity. Different mechanism leading to increased thermal conductivity at high temperatures observed and discussed. Mixtures of silicon and germanium, lead selenide and lead telluride were studied.

215. IYENGAR, B. R. Y. **Measurement of vapor pressures by the Hill-Blades thermoelectric technique.** *J. Sci. and Indus. Res.* (*India*), **13B**: 73–75, 1954.

Selected previous work is reviewed and re-evaluated.

216. JOHANSSON, C. H. and LINDE, J. O. **Crystal structure, electrical resistance, thermoelectric power, heat conductivity, magnetic susceptibility, hardness and "tempering" phenomena of the AuPt system in connection with the phase diagram.** *Ann. Physik*. **5**: 762–792, 1930.

In German. Trans No. 59–20252 available from SLA or LC.

217. JOHNSTON, JOHN and ADAMS, L. H. **The influence of pressure on the melting points of certain metals.** *Am. J. Sci.* **31**: 501–517, tables, June 1911.

Table II, p. 513 gives the observed reading of the thermoelectric emf at the freezing point for tin, lead, cadmium, and bismuth.

218. JONES, F. L. **Fundamental processes of electrical contact phenomena.** *Gt. Brit., Scientific and Industrial Research.* Radio Research Special Rpt. **24**, 66 p., 1953.

"A comprehensive critical survey of existing knowledge of electrical contact phenomena and of the fundamental physical processes underlying contact operation and failure for all types of contact. A rigorous mathematical treatment of the role of the Thomson effect in fine transfer and the location of the maximum temperature in a contact is given. Research into the elimination of fine transfer based on investigations of the Thomson coefficient and thermal and electrical coefficients at all temperatures up to the boiling point and studies of the properties of bimetal contacts are indicated.

219. KAGANOV, M. I. and TSUKERNIK, V. M. **Influence of thermoelectric forces on the skin effect in metals.** *Zhurn. Eksp. i Teor. Fiz.* **35**: 474–478, Aug. 1958.

In Russian.

Translation in *Soviet Phys. JETP* **35**: 327–330, Feb. 1959.

The surface impedance of a metal is computed allowing for the thermoelectric forces.

220. KAMMER, E. W. **Changes in thermoelectric power of copper with cold work at liquid nitrogen temperature.** *Phys. Rev.* **104**: 265, Oct. 1, 1956.

An illustration shows variations produced in the thermoelectric power of copper by plastic elongation at liquid nitrogen temperature.

In contrast to previous experiments the wires were plastically deformed at 7K and measurements were made at this temperature. By this means the annealing of defects introduced when the deformation is carried out at 290 K is reduced. Two annealing processes which affect thermoelectric power in opposite senses are identified.

221. KAMMER, E. W. **Changes in thermoelectric power of silver and gold with cold work at liquid nitrogen temperature.** *J. Appl. Phys.* **29**: 1122, Jly. 1958.

In contrast to previous experiments the wires were plastically deformed at 7°K and measurements were made at this temperature. By this means the annealing of defects introduced when the deformation is carried out at 290°K is reduced. Two annealing processes which affect thermoelectric power in opposite senses are identified.

222. KAMMER, E. W., SALKOVITZ, E. I. and SCHINDLER, A. I. **Brillouin zone studies. V. Thermoelectric power of dilute magnesium alloys.** *Phys. Rev.* **100**: 1257, 1955.

Abstract only of paper given at meeting of the American Physical Society, Chicago, Ill., November 25-26, 1955.

At room temperature the elements Li, Al, Ag, Cd, In, Sn, Tl, and Pb form terminal substitutional solid solutions in Mg. Salkovitz and Schindler have suggested that Brillouin zone overlap in these systems may be studied by observing various transport phenomena as a function of alloying additions. Such a study has now been made on the effect of these alloying additions upon the thermoelectric power. It is found that a reversal in electrical polarity occurs at low concentrations for additions of the tri- or tetra-valent additions near the region of overlap. The ratio of thermoelectric power to atomic percent impurity element is a cyclic function of atomic number. For concentrations greater than those characterised by initial overlap conditions these cycles are in phase with the valence series of the periodic table. Resistivity and Hall effect measurements on these alloys are compared for correlations of behaviour at the Brillouin zone overlap concentrations.

223. KAMMER, E. W., SALKOVITZ, E. I. and SCHINDLER, A. I. **Brillouin zone studies. VIII. Thermoelectric power of dilute magnesium alloys.** *Am. Phys. Soc. Bull.* **1**: 257–258, June 21, 1956.

Abstract of paper.

Concerns thermoelectric power measurements at liquid nitrogen temperature on magnesium alloys containing silver and cadmium, the latter element producing no change in the valence electronic per atom ratio.

224. KAMMER, E. W. and SALKOVITZ, E. I. **Studies of shock propagation, vibration and their instrumentation.** *In U.S. Nav. Res. Lab. Rept. NRL Prog.* p. 30–31, fig., Jly, 1959.

Concerns relative thermoelectric power of magnesium alloys with respect to pure magnesium as a function of the atomic percent of substitutional additions.

225. KAMMER, E. W. and SALKOVITZ, E. I. **Studies of shock propagation, vibration and their instrumentation.** *U.S. Naval Res. Lab. Rpt. NRL Prog.*, p. 33–34, fig., Dec. 1958.

Progress report on a programme concerning effects of impurities and lattice imperfections on thethermoelectric potentials of metals. A figure indicates thermoelectric power of indium substitutional alloys as a function of valence electrons per atom.

226. KAMMER, E. W. and SALKOVITZ, E. I. **Studies of shock propagation, vibration and their instrumentation.** *In U.S. Navy Res. Lab. Rept. NRL Prog.* p. 38–39, Aug. 1959.

Concerns relative thermoelectric power of indium binary alloys with tin and lead susbtitutions at 0°C.

227. KAMMER, E. W. and SCHINDLER, A. I. **Studies of shock propagation, vibration, and their instrumentation.** *U.S. Nav. Res. Lab. Rpt. NRL Prog.*, p. 24, Feb. 1959.

Concerns that part of a programme for developing instrumentation to be used in the measurement of shock and vibration which includes effects of impurities and lattice imperfections on the thermoelectric potentials of metals.

A figure shows the absolute thermoelectric power of palladium saturated with hydrogen as a function of temperature. Superimposed upon this figure, for comparison, is the resistivity curve. It is seen that a marked change occurs in the thermoelectric power curve for the temperature range including the resistivity maximum.

228. KAMMERER, C. **On the graphical determination of thermoelectric effects and relations.** *Elektrotech. u. Maschinenbau.* **66**: 349–352, Dec. 1949.

In German.

The nature of thermoelectric effects in metal/metal couples is discussed, with reference to the magnitudes of thermoelectric powers of several metals against Pb, the values of Thomson coefficients, and of Peltier heats. The recent ideas on thermoelectricity based on the concept of entropy flow are developed and the results used to construct a thermoelectric diagram for several metals from which the thermoelectric properties for any couple may be calculated.

229. KAPUSTINSKII, A. F. **Electronegativity of metals and certain properties of metallic solutions.** *In* the Physical Chemistry of Metallic Solutions and Intermetallic Compounds. Proceedings of a Symposium held at the National Physical Laboratory on 4th, 5th and 6th June 1958, volume 1, 2J, p. 2–5, London, H.M. Stationery Office, 1959. (National Physical Laboratory Symposium no. 9)

A brief account is given of the connection between the Volta potentials, the photoelectric and thermoelectric effects respectively of pure metals, and their electronegativities.

230. KEESOM, W. H. and MATTHIJS, C. J. **Thermoelectromotive forces of a superconductor against the same metal in the non-superconductive state,** *Physica* **5**: 437–448, figs., May 1938.

In connection with the fact that the thermoelectromotive forces in a thermocouple consisting of a superconductor A and another metal B, are affected by a magnetic field, we have examined whether there is a thermoelectromotive force in a thermocouple in which the metal B has been replaced by the same metal A but with superconductivity disturbed by a magnetic field. Experiments were made on tin and on indium. For both metals a thermoelectromotive force as mentioned was found. For indium the agreement with the results of the earlier experiment is good. For tin such a comparison could not be made for want of experimental data. The results of the present experiment were further compared with the formula for the thermoelectromotive force for this case given by Kok, and on broad lines agreement was found.

231. KEESOM, W. H. and MATTHIJS, C. J. **Thermoelectromotive forces of some superconductors in the neighborhood of their transition points: the influence of a magnetic field.** *Physica*, **5**: 1–16, figs., Jan. 1938.

Thermoelectromotive forces of lead against a silver alloy-normal and against tin, and of indium against lead were measured at temperatures obtainable with liquid helium and with liquid hydrogen. The influence of a magnetic field was examined. The thermoelectromotive force between two super conductors is zero, also when a magnetic field, smaller than the threshold values for the two metals, is applied. The curve E (thermoelectromotive force) versus T for temperatures above the transition point of one of the two metals is shifted by the application of a magnetic field, in connection with the shifting the transition point undergoes. The curve E (thermoelectric power) versus T is continuous at the transition point as well in a magnetic field as when no magnetic field is applied; de/dT, however, is discontinuous in both cases. In a region of about one to two degrees above the transition point, either in a magnetic field or not, E varies with the (longitudinal) magnetic field.

232. KELVIN, W. T. **On the effects of mechanical strain on the thermoelectric qualities of metals.** *In* his Mathematical and Physical Papers, v. II, p. 173–174, Cambridge, University Press, 1884.

Brief description of experimental investigation of thermoelectric effects of mechanical strains.

233. KELVIN, W. T. **On the electro-dynamic qualities of metals.** [The Bakerian Lecture]. *In* his Mathematical and Physical Papers, v. II, p. 189–395, Cambridge, University Press, 1884.

There is a section on thermoelectric inversions including theoretical inferences regarding electrical convections of heat, from facts of thermoelectric inversions.

Part II is entitled Effects of Mechanical Strain and of Magnetisation on the Thermoelectric Qualities of Metals.

234. KELVIN, W. T. **On the thermoelectric position of aluminium.** In his Mathematical and Physical Papers, v. II, p. 181, Cambridge University Press, 1884.

Brief report of investigation of thermoelectric properties of aluminium.

235. KIKUCHI, M. and ONISHI, T. **A thermoelectric study of the electrical forming of germanium rectifiers.** *J. Appl. Phys.* **24**: 162–166, Feb. 1953.

Experimental methods described by Granville and Hogarth were applied. Remarkable improvements in the I/V characteristics were obtained by applying appropriate alternating forming voltages. Using n-type crystals, the thermoelectric current observed on the etched surface was converted by the forming from n-type to p-type. The dependence of the thermo-emf on the contact pressure is greatly increased by the forming. The results indicate that a substance with relatively high resistivity and p-type thermo-emf is formed between the point contact and the Ge surface.

236. KOHLER, MAX. **The relation between the isothermal and adiabatic Ettingshausen-Nernst coefficient.** *Z. Physik.* **118**: 312–316, 1941.

In German,

When heat flows through a transversely magnetised metal plate, a transverse electric p.d. is set up corresponding to the Ettingshausen-Nernst effect. N. H. Frank deduced that the adiabatic Ettingshausen–Nernst constant = 2 x isothermal constant, which is not in accord with the experimental evidence. The author, by considering the thermoelectric field strength at the connecting wires in the adiabatic cases, finds the adiabatic constant = isothermal constant, provided the plate and connecting wires are of similar material and the thermal forces between magnetised and non-magnetised metal are small.

237. KOHLER, MAX. **The suppression of the thermoelectric effect at very low temperatures.** *Braunschw. Wiss. Ges. Abh.* **3**: 49–54, 1951.

In German.

The thermoelectric phenomena of electronic conductors are considered using only the 3 principal laws of thermodynamics.

238. KOPETS, Z. **Effective mass of electrons and holes in germanium.** *Zhurn. Tekh. Fiz.* **26**: 2451–2458, Nov. 1956.

In Russian.

The effective mass is calculated from experimental data on the thermo-emf α, Hall constant, and electrical conductivity, for the case when α increases with temperature. At a temperature of 125 K and electron concentration of $2{\cdot}7 \times 10^{-15}$ the effective electron mass of the hole is 0·23 at a hole concentration of $1{\cdot}3 \times 10^{17}$. Results of effective electron and hole mass calculations are tabulated for concentrations of $2{\cdot}7 \times 10^{15}$-$6{\cdot}6 \times 10^{17}$ and $1{\cdot}3 \times 10^{17}$-$5{\cdot}5 \times 10^{18}$, respectively, at temperatures between 125 and 250 K

239. KORZH, P. D. **Opredelenie zheleza v bimetallcheskikh (med'-stal) slitkakh i provoloke termoelektricheskim metodom. (Determination of iron in bimetallic (copper-steel) bars and rods by the thermoelectric method).** *Zavodskaya Lab.* **22**: 1076–1078, Sept. 1956.

In Russian.

Thermoelectric determination of Fe contamination in the Cu in bimetallic Cu–steel bars. Dependence of the thermoelectromotive force on temperature and concentration of Fe in the alloy.

240. KORZH, P. D. and ERSHOVA, A. P. **Termoelektricheskii metod opredeleniia ugleroda v stali po khodu plavki. (Thermoelectric method for determining the carbon in steel in the course of smelting).** *Zavodskaya Lab.* **24**: 41–43, 1958.

In Russian. Henry Brutcher translation no. 4265.

Samples of rimming steel were taken every 101–5 minutes from the open-hearth furnace. Analysis was based on the fact that C is the only element that does not change quantitatively in the course of smelting.

241. KUHRT, F. and MAAZ, K. **Hall voltage generators.** U.S. Patent 2,855,549, filed Sept. 10, 1956, issued Oct. 7, 1958.

A Hall voltage generator which can operate in a magnetic field in an area where a high temperature gradient exists without having thermoelectric voltages interfere with the Hall output is described. Compensation for the thermoelectric voltages is achieved by using as the Hall electrode which is immediately adjacent to the generator the same semiconducting material as in the generator. (Semiconductor Electron **2**: 3222, Jan. 1959).

242. KUNIN, N. F. **Change of thermo-emf of metals under plastic deformation.** *Fiz. Metal. i Metalloved.* **2**: 237–243, 1956.

In Russian.

"When a metal undergoes plastic deformation (D), a thermo-emf is generated because of the change in the thermoelectric properties of the metal.

243. KUNIN, N. F. and IAKOVLEV, M. A. **Elimination of induced thermo-emf in copper.** *Fiz. Metal. i. Metalloved.* **2**: 418–422, 1956.

In Russian. Not examined.

The elimination of induced thermo-emf's in copper after differing degrees of preliminary deformation (plastic torsion) and annealing at different temperatures has been studied. As the annealing temperature decreases the stability of the emf increases considerably. During annealing, the emf decreases a gradually decreasing rate, towards a constant value which decreases with increase in the deformation. It is suggested that the initial deformation determines the course of recovery.

244. KUNIN, N. F. and MELAMED, I. Z. **Measurement of thermal emf of metals of the copper sub-group under the influence of plastic deformation at various temperatures.** *Fiz. Metall. i Metalloved.* **2**: 423–427, 1956.

In Russian. Not examined.

Cu, Ag and Au under 40–50% deformation at various temperatures have induced thermal emf proportional to the magnitude of the relative deformation. Other conditions being equal, thermal emf diminishes with increasing temperature.

245. LEAF, BORIS. **Phenomenoligical theory of transport processes in fluids.** *Phys. Rev.* **70**: 748–758, 1946.

246. MADELUNG, OTFRIED. **Thermoelektrische und thermomagnetische effekte in halbleitern. (Thermoelectric and thermomagnetic effects in semiconductors).** *In* International Colloquium on Semiconductors & Phosphors, 1956, Proceedings, p. 178–183, New York, Interscience Publishers, 1958.

In German.

General discussion of the origin of isothermal and non-isothermal effects in impurity and intrinsic semiconductors.

247. MARGOLIN, J. M. **Thermoelectric investigation of some processes occurring in alloys. I.** *Zhurn. Tekh. Fiz.* **18**: 61–70, Jan. 1948.

In Russian.

The changes of the thermo-emf were investigated for various carbon-steels and alloy steels after varied heat treatments, annealing and tempering. Some erroneous conclusions about the hysteresis of the thermo-emf drawn by Bakhmetiov (1897) were refuted. Relations between hysteresis and the thermal transformations are plotted for the individual materials investigated. The complex nature of the processes taking place, *e.g.*, during the cooling down of a particular steel from 720° to 120°C, is well brought out by the graph of the emf. Numerical differentiation of the original curves enables accurate values of the singular points of these processes to be found, which may then be reproduced by automatic recording of the emf, this being only one example of the usefulness of the method.

248. MARKOV, B. F. **The electromotive forces of thermocircuits with molten salts.** *Akad. Nauk. SSSR. Dok.* **108**: 115–117, 1956.

In Russian.

These were measured for molten silver halides by themselves as well as mixed with those of alkali metals. The sequence of emf's reverses that of solid salts, *i.e.*, it decreases from AgI to AgBr to AgCl. Following Wagner the heterogeneous effect is estimated thermodynamically. For this it suffices to determine the entropy of silver and the molten silver halides at the experimental temperature. The homogeneous effect decreases similarly to the solid case, from AgCl to AgBr to AgI; the absolute temperature coefficients decrease in the same sequence.

249. MEIXNER, J. **Electrical properties of solids. VII. Galvanomagnetic, thermoelectric effects.** *FIAT Rev. German. Sci.* 1939–1946, (Office Military Gov't. German) "Physics of Solids II," p. 131–142, 1948.

In German.

A generalized thermodynamic theory for all the effects, due to Meixner, is outlined. Other theoretical work includes the dependence of thermoelectric power on the orientation of the specimen crystal, on contact emf's between metals, and on the isotropic nature of the electron gas. Experimental results for the effects in various metals and semiconductors are quoted. The Hall effect in PbS and in a–Ag_2S is measured and it is confirmed that a–Ag_2S is an excess semiconductor.

250. MAYER, H. **Recent developments in conduction phenomen in thin metal films.** *In* International Conference on Structure and Properties of Thin Films, Bolton Landing, N. Y. Proceedings, p. 225–252, New York, Wiley, 1959.

Energy dependence of the mean free path and thermoelectric power is discussed, p. 240–243.

251. MELAMED, I. Z. **Additivity of the thermoelectric effects produced by the super-position of deformations of the same type.** *In* Symposium *Nauch. Trudy Kuibyshevsk. Indus. Inst. No.* **6**: 197–200, 1956.

In Russian. Not examined.

"The 'induced' thermo-emf's in couples consisting of the same metal, one wire being annealed, and the other deformed, have been measured. The 'induced' thermo-emf for copper deformed at room temperature is proportional to the relative deformation. This proportionality persists for copper deformed between −192 and +364°C, and is also observed for silver and gold, deformed at room temperature. The emf is due to the accumulation of lattice distortions. For the same rates and temperatures the thermo-emf is additive with respect to the deformation. This was checked on copper wires 0·9 mm diameter and 200 mm long by twisting them to various extents and at different temperatures. It was found that the emf's are additive only if (after preliminary deformation occurs at a lower temperature than the preceding, otherwise the total emf is less than that calculated (on the assumption of additivity). It is concluded that the emf of the unstrained metal at the time of its deformation determines the residual thermoelectric state of a plastically deformed metal." *J. Abs. Metall. Nos.* **5** to **8**: 182, 1957.

252. MELAMED, I. Z. **Effect of the temperatures of plastic deformation of copper on its mechanical and thermoelectric properties.** *In* Symposium: *Nauch. Trudy Kuibyshevsk Indus. No.* **7(a)**: 137–142, 1957.

In Russian. Not examined.

"The influence was considered of the deformation temperature on the mechanical and thermoelectric properties of copper."

253. MELAMED, I. Z. **A simple theory of induced thermoelectric forces.** *In* Symposium: *Nauch. Trudy Kuibyshevsk. Indus. Inst. No.* **6**: 191–195, 1956.

In Russian. Not examined.

"Theoretical calculation is made of the thermoelectromotive force in a chemically homogeneous thermocouple, the elements of which differ only in the degree of preliminary deformation (physically heterogeneous circuit)."

254. MEL'NIK, V. G., MEL'NIK, I. G. and GUTIN, S. S. **On p-n junction in solid point-contact rectifiers.** *Akad. Nauk. SSSR. Dok.* **121**: 852–854, May 1958.

In Russian.

The thermo-emf and current-voltage characteristics of n-type Ge and Si point-contact rectifiers before and after electroforming were studied on experimental models in which thin metallic threads had been welded on to the point-contact wires. The threads were heated by electric current to 500–600°C and the thermal front thus produced moved along the contact wires to the Ge and Si crystals. An inversion of sign of the thermo-emf observed after electroforming both in Ge and Si was taken to indicate passage of the thermal front from a region of p-type conductivity to one characterized by n-type conductivity, and it was concluded that while the rectifying action of point-contact diodes before electroforming is due to different contact potentials of the metal and semiconductor, the improved rectifying characteristics after electroforming are due to the existence of a p-n junction formed as the results of the electroforming treatment.

255. Michigan State University. East Lansing Mich. **Thermoelectric power of cold-rolled pure copper,** by R. H. KROPSCHOT and F. J. BLATT. 17 p., Mar. 1, 1959 (Interim Tech. Rept. 2) (Contract DA20-018-ord-16883). (AD 220 469).

The difference between the thermoelectric power (TE) of severely cold-rolled and well annealed pure copper has been measured between about 8°K and 320°K. The absolute TE of annealed and cold-worked samples were determined over the same temperature range by measuring the TE of a thermocouple formed from annealed copper and pure lead. The TE of cold-rolled copper is positive relative to annealed pure copper over the entire temperature range, and the effect of cold work is largest at very low temperatures where the TE of annealed copper displays a pronounced minimum.

256. MOREAU, C. and LEPOUTRE, G. **Thermoelectric effect in electrolytes. I. Thermodynamical investigation.** *J. Chim. Phys.* **52**: 498–502, June 1955.

In French.

A complete thermodynamical treatment, starting with thermostatics, of irreversible phenomena occurring in a system which consists of two identical reversible electrodes maintained at different temperatures and immersed in a solution containing several kinds of ions. Different transport values (transference numbers of the solvent, transported entropy and heat) are defined and explained. The results obtained are applied to express some thermoelectric phenomena (Peltier effect, Thomson effect).

257. MORI, HAZOME. **Statistical-mechanical theory of transport in fluids.** *Phys. Rev.* **112**: 1829–1842, Dec. 15, 1958.

The application of the present theory to the problem of thermoelectricity yields the same expression for the static electrical conductivity as Kubo's theory.

258. MORTLOCK, A. J. **The effect of tension on the thermoelectric properties of metals.** *Austral. J. Phys.* **6**: 410–419, Dec. 1953.

Author measured effect of elastic strain on thermoelectric power of copper, gold, silver, platinum, palladium, nickel, aluminium, titanium, molybdenum, iron, and tungsten. One leg of a single-wire thermocouple circuit was stressed, in various increments, while the junction temperature differences were varied from 40° to 400°C. The results obtained for gold are not in agreement with results reported by G. S. Meyer.

259. MUKHERJEE, J. K. and CHATTERJEE, G. P. **Some studies of recovery and oxidation characteristics of copper by thermoelectric phenomena.** *In* 1954 Symposium on Non-Ferrous Metal Industry in India, p. 293–297, 1957.

Authors show that changes in the thermoelectric properties can be used to detect changes during the recovery stage of cold-worked materials.

260. MUKHERJEE, J. K. and CHATTERJEE, G. P. **Tempering of carbon steel samples by thermoelectromotive forces.** *India Inst. Metals Trans.* **8**: 217–224, 1954/1955.

The emf against constantan is reported for a 018% C steel wire H_2O—quenched from 1000° and tempered at 50° or 75° for 1 to 3 hours. The plots of emf vs. tempering time at given temperature show definite maximum and minimum.

261. MULLER, HORST-GUIDO and MUTH, PETER. **Investigation on the "k-state".** *Z. Metallk.* **50**: 217–224, Apr. 1959.

In German.

Resistivity, differential thermoelectric voltage and Hall constant of Ni-Cr and Ni-Cr-Fe alloys measured after varying heat treatments and following varying degrees of cold deformation. A theory explaining the behaviour in the "K-state" is developed.

262. MUSER, H. A. **Thermoelectric force measurements on illuminated lead sulphide.** *Z. Physik.* **144**: 56–65, Jan. 17, 1956.

In German.

Experiments indicate that the true thermoelectric force is not affected by illumination; apparent variations of thermoelectric force are due to photovoltaic effects.

263. Naval Research Laboratory, Washington, D.C. **The Friedel theory of thermoelectric power applied to dilute magnesium alloys,** by E. I. SALKOVITZ, A. I. SCHINDLER and E. W. KAMMER. 8 p., illus., Jly. 26, 1957. (Rept. 4968). (AD–139 581).

Several theories of the thermoelectric power of alloys have been developed, all based on Mott's original analysis. Of these theories, that of Friedel seem to best fit the data for alloys of monovalent metals. This theory states that $\triangle X$ is equal to $-(E_F - E_O)\,\delta \log \triangle\gamma/\delta E$ and is equal to a constant. In its application to dilute alloys of magnesium, it is found to work quite well. In addition, it is shown that for these alloys, the parameter $\triangle X$ takes on values which depend upon the valence of the solute atom. A dependence upon the atomic number of the solute is also indicated.

264. Naval Research Laboratory, Washington, D.C. **Wave propagation in suspensions,** by W. S. AMENT. 114 p., tables, Apr. 9, 1959. (Rpt. 5307).

This report deals with theoretical methods for determining the effective physical properties of suspensions or statistical mixtures of spherical particles of different isotropic materials. The methods are shown sufficiently general to allow estimates of secondary physical effects such as the average optical rotary power, the thermoelectric power, and the acoustic attenuation of appropriate suspensions.

265. New York Naval Shipyard. Material Laboratory, Brooklyn, N.Y. **Applicability of thermoelectric comparator to the identification of steel plate materials.** Final Technical Evaluation Report, by F. Bernstein. 15 p., illus., May 22, 1957. (AD—143 589).

An evaluation has been made of the applicability of instrumentation utilizing thermoelectric potentials to the identification of steel plate materials. A given type of plate material was found to be characterized by a range of thermoelectric potentials. Of the six types of plates tested, the ranges for four of these showed considerable overlapping and only Grade M plate under $\frac{7}{8}$ in. thick was clearly separable from the others. It is concluded that the instrumentation is not suitable for general sorting or identification of steel plate materials, but may be utilized for problems where the number of possibilities is limited.

266. New York University, College of Engineering, New York, N.Y. **Thermoelectric properties of intermetallic compounds.** 2 p., Aug. 31, 1959. (Prog. Rept. 11). (Contract AF33-(616)3883). (AD–227 559).

Determinations of various properties were initiated for the compounds BaSe and SnTe. The room temperature resistivity of BaSe was 10^{10} ohm-cm; it decreased with increasing temperature. The resistivity temperature curve of BaSe had the same slope as that of BaTe. The Sn-Te phase diagram in the region near the compound SnTe was redetermined. The congruent melting of SnTe at 806·5°C was confirmed. In the pseudobinary SnTe-PbTe, single crystals were grown with an over-all composition of stoichiometric SnTe, $Sn._9Pb._1$–Te, $Sn._3Pb._7Te$. The crystals were grown by the Bridgman technique at a lowering rate of 0·5 cm/hr. The room temperature resistivity of SnTe was 10^{-4} ohm-cm. (TAB p. 475, Feb. 1, 1960).

267. NOBE, KEN and SEYER, W. F. **Effect of torsional stress on the electrode potential of copper.** *J. Appl. Phys.* **29:** 1632–1634, 1958.

Measurements of the emf of a galvanic cell with a stressed metal electrode and an unstressed one show that the emf of hard-drawn Cu electrodes varies within the elastic limit as the square of the torque and the torsional stress; Taylor and Quinney's results (Roy. *Soc. Proc.* **143**: 307, 1934), when converted to electrochemical units, show close agreement with the values obtained. Negative emf measurements indicate that the stressed electrode is more anodic than the unstressed one.

268. NOBE, KEN, MINIATO, O. K. and SEYER, W. F. **Stress and electropotential of copper wires.** *Am. Inst. Mining Engrs. Met. Soc. Trans.* **212**: 884–889, 1958.

The emf produced by applying a tensile stress, σ, to one of a pair of electrolytic (99·29%) Cu wires in M-NaCl and 0·1 M-$CuSO_4$ solution was measured under restricted-flow conditions. For annealed Cu within the region where Hooke's law applies, emf $\propto \sigma^2$, as predicted by theory, and the process is reversible, while for cold-worked material, emf $\propto \sigma$, and again the process is reversible. Where σ is sufficient to cause plastic deformation the emf decreases, and the process is irreversible. The results are discussed in relation to thermodynamical considerations.

269. ONSAGER, LARS. **Reciprocal relations in irreversible processes. I.** *Phys. Rev.* **37**: 405–426, Feb. 15, 1931.

Examples of coupled irreversible processes like the thermoelectric phenomena, the transference phenomena in electrolytes and heat conduction in an anisotropic medium are considered.

270. OOIJEN, D. J. **The thermoelectric power of copper, silver and gold after coldworking.** 126 p., Delft, Holland, Uitgeverig Excelsior, 1957.

The thermoelectric power of Cu, Ag and Au wires which had been cold-worked by drawing at room temperature was measured against undeformed wires of the same material from helium up to room temperature. The increase in resistivity before any recovery process had taken place was also measured. The change in the differential thermoelectric power and of the resistivity was then followed through the recovery process brought

about by slow annealing at various temperatures up to 100°C. The theory of the thermoelectric effects appropriate to the experiments is extended to cover the experimental conditions, and two independent electron scattering mechanisms are considered. The experimental results are most satisfactorily interpreted in terms of formulas due to Friedel.

271. OTTER, F. A., Jr., FLANDERS, P. J. and KLOKHOLM, E. **Ferromagnetism in noble metal alloys containing manganese.** *Frank. Inst. J.* **260**: 75–76, 1955.

The thermoelectric properties of alloys of Au and Ag with Mn were investigated. Nonlinear deviations in the temperature dependence of the electric resistivity, characteristic of ferromagnetic alloys, were observed for those alloys containing more than 8 at. % Mn, magnetic measurements on the alloys Au+18·64 at. % Mn, Au+13·01 at. % Mn, and Ag+14·58 at. % Mn showed that they were ferromagnetic with Curie temperatures of 317°, 139°, and 163°K, respectively.

272. PARROTT, J. E. **The interaction of electrons and phonons in semiconductor transport phenomena.** *In* Semiconductors and Phosphors, Proceedings of International Colloquium held in Garmish-Partenkirchen, 1956, p. 495–496, Brunswick, Vieweg, 1958.

Not examined.

"It is found that the application of the 'electron-phonon drag' analysis to the electrical and thermal conductivity of Ge does not produce such large effects as it does on the thermoelectric properties." *Sci. Abs.* **62A**: 10969, 1959.

273. PEARSON, W. B. **The valence state of metallic lead.** *Can. J. Phys.* **36**: 631–632, May 1958.

Attention is drawn to the fact that the thermoelectric and resistive measurements of dilute lead alloys, containing various solute proportions, indicate that a homovalent impurity in lead is an atom lying in Group IV, and not in Group II.

274. PERRIER, ALBERT. **Thermal-electric energy transformations in anisotropic conduction.** *Helv. Phys. Acta.* **29**: 206–209, 1956.

Possibility of direct conversion of heat into electrical energy is considered from a new point of view.

275. PFANN, W. G., BENSON, K. E. and WERNICK, J. H. **Some aspects of Peltier heating at liquid-solid interfaces in germanium.** *J. Electron.* **2**: 597–608, May 1957.

Peltier heating at a liquid-solid interface has unique advantages in controlling crystal growth processes in semiconductors and certain metals. The heat effect is produced at the interface without time-lag and can be reversed by reversing the current. Uses in growing single crystals, in producing n-p-n and n-p-n-p junctions in semiconductors, and in temperature gradient zone melting are discussed.

276. PHILIBERT, J. and CRUSSARD, C. **Kinetics of the martensite transformation in a hypereutectoid steel.** *Iron & Steel Inst. J.* **180**: 39–48, 1955.

The decomposition behaviour at sub-zero temperatures of a 1·4%—C, 2·5%—Cr steel initially quenched at 20° has been studied. There is no "athermal" nucleation, but rather a classical type of random nulceation caused by thermal changes. The apparently athermal nucleation of the martensitic transformation is explained by the particularly high rate of nucleation in the region M_s–M_f. Theoretical calculations allow this high rate of nucleation to be allowed for satisfactorily, and justify the invariance of M_s with the highest rates of cooling reached in Greninger's experiments. The thermoelectric power varies linearly with the percentage of martensite.

277. PICKER, AMOS. **"Sounds" of atoms.** *Stanford Res. Inst. J.* **4**: 27–30, First Quarter 1960.

In this article on physical acoustics, wherein researchers use beams of sound to probe secrets of atoms the statement is made that "workers in such frontier fields as liquid thermoelectric materials and pressure sensitive chemical reactions will find that an acoustical probe beam can supply basic information not easily available otherwise.

278. PIKUS, G. E. **On the thermoelectric properties of semiconductors.** *Zhurn. Eksp. Teor. Fiz.* **21**: 852–853, 1951.

In Russian.

It is shown that the "Gurevich effect" (an additional thermo-emf associated with temperature gradients) is negligible for semiconductors.

279. PIKUS, G. E. **Thermo- and galvano-magnetic effects in semiconductors taking account of variations in carrier concentration. I. Thermo- and galvano-magnetic effects in weak fields.** *Zhurn. Tekh. Fiz.* **26**: 22–35, 1956.

In Russian.

Extensive calculations taking account of recombinations in the bulk and at the surface for some simply shaped specimens when the fields are so weak that the carrier concentration is only slightly different from its equilibrium value. The following effects are discussed: thermoelectric power, Hall effect, magneto-resistance, electrical resistance in a temperature gradient, the Ettingshausen effect, and behaviour in oscillating fields.

280. PIKUS, G. E. **Thermo- and galvano-magnetic effects in semiconductors taking account of variations in carrier concentration. II. Galvanomagnetic effects in strong fields. Thermal conductivity of electrons and excitons.** *Zhurn. Tekh. Fiz.* **26**: 36–50, 1956.

In Russian.

Continuation of Part I. Treats electrical conductivity, Hall effect, magnetoresistance, electronic thermal conductivity and the transport of heat by excitons.

281. POMEY, GILLES AND PHILIBERT, JEAN. **Thermoelectric study of the transformations in iron-chromium alloys.** *Acad. Sci. Paris. Compt. Rend.* **241**: 977–979, 1955.

In French.

The measurement of the thermo-electric power permits following the evolution of Fe–Cr alloys in the neighbourhood of the equiatomic composition and the differentiation of the transformations; order–disorder and $\alpha \rightleftharpoons \sigma$.

282. RADCHIK, A. S. NIKIFOROV, I. P. and SHTAIGER, E. V. **Registration of wear, moment of friction and temperature during the process of wear, with the help of resistance-wire devices.** Symposium Povyshenie Iznosostoikosti i Skora Sluzhby Mashin, Kiev and Moscow, Mashgiz, 182, 1956.

In Russian. Not examined.

"A method for the simultaneous registration, without stopping the experimental machine, of wear and the coefficient of friction has been worked out. The experiments are carried out on a facing type of machine. Wear is determined with the help of resistance-wire devices (PDS) stuck on to the arm taking up the bending pressure from the specimen (which changes with specimen wear), the coefficient of friction is determined with the help of PDS stuck on to the arm which takes up the pressure from the barrel with a balance arm carried along by frictional forces; the temperature at the surface contact is determined by thermo-electrical means." *J. Abs. Metall. Nos.* **5** *to* **8**: 457, 1957.

283. RICHARDS, T. L., PUGH, S. F. and STOKES, H. J. **The kinetics of recovery and recrystallization of copper from hardness and thermoelectric-power measurements.** *Acta Met.* **4**: 75–83, figs., Jan. 1956.

Annealing of H.C. copper strip cold-rolled with reductions in thickness to 50% and 96% has been studied as a rate-process by parallel observations of changes in hardness and thermoelectric power. In accordance with earlier investigations, thermo-electric power is assumed to be directly related to residual elastic lattice strain. While the hardness—isothermal annealing curve of strip rolled 50% exhibits a definite discontinuity indicative of two processes the thermoelectric power curve is, in agreement with Brindley's earlier conclusion, pseudo first order.

284. RUDNITSKII, A. A. **Thermoelectric method of studying transformations in metals and alloys.** *Zhurn. Neorgan. Khim.* **1**: 1305–1321, 1956.

In Russian.

"In order to study transformation in metals and alloys in the solid state using N. S. Kurnakov's pyrometer the values of thermal-emf were recorded in relation to the temperature.

285. SAENTZ, A. W. **Changes in the electrical, thermal, and thermoelectrical properties of monovalent metals by lattice distortions.** *Phys. Rev.* **91**: 1142–1151, Sept. 1, 1953.

A transport equation is derived for the distribution of conduction electrons in monovalent metals with static lattice distortions, simple assumptions regarding interaction energy being made. Using an iteration method, and considering temperatures very much higher than the Debye temperature of the lattice, a set of integral equations is obtained and solved explicitly. General expressions are found for the resistivity, thermal conductivity and absolute thermoelectric power tensors and are applied to specific calculations for a metal having an array of parallel positive-negative edge dislocations.

286. SALKOVITZ, E. I. and KAMMER, E. W. **Basic studies of the metallic state (Brillouin zone studies of ternary magnesium alloys).** *U.S. Nav. Res. Lab. Rept. NRL Prog.* p. 38–39, figs., June 1959.

In earlier work it was demonstrated that the electron contribution of the thermoelectric power was a linear function of the electron concentration in the binary alloys studied. This behaviour was interpreted in terms of Brillouin Zone overlap. A new investigation is now reported to determine to what extent the model may be applied to dilute ternary alloys of magnesium.

A figure shows relative thermoelectric power of magnesium alloys with respect to pure magnesium as a function of the atomic percent of substitutional additions.

287. SALKOVITZ, E. I. and KAMMER, E. W. **Thermoelectric power of magnesium ternary alloys.** *Am. Phys. Soc. Bull.* **4**: 412, Nov. 27, 1959.

Abstract of paper.

In an investigation of dilute ternary alloys of magnesium it was found that the thermoelectric power curve strongly resembles that of the MgCd series.

288. SALKOVITZ, E. I., SCHINDLER, A. I. and KAMMER, E. W. **Transport properties of dilute binary magnesium alloys.** *Phys. Rev.* **105**: 887–896, illus., Feb. 1, 1957.

It is the main purpose of this paper to evaluate in terms of the overlap model extensive measurements of the resistivity, the thermal variation of resistivity Hall coefficient, and thermoelectric power for a series of dilute magnesium alloys. A secondary goal is to check the validity of Mattheissen's rule and Linde's rule for these alloys.

289. SALKOVITZ, E. I., SCHINDLER, A. I. and KAMMER, E. W. **Friedel theory of thermoelectric power applied to dilute magnesium alloys.** *Phys. Rev.* **107**: 1549–1552, Sept. 15, 1957.

Theories of the thermoelectric power of alloys are reviewed. Friedel's theory applies to several dilute binary solid solutions of Mg, the parameter $\triangle_x = -(\varepsilon_f - E_0)$ 5 log $\triangle$ p/δE) being constant for a given alloy up to the neighbourhood of the solubility limit of the alloy in question. $\triangle_x$ also depends on the valence of the solute atom and bears some relation to the atomic number of the solute.

290. SAMOILOVICH, A. G. and KLINGER, M. I. **On the theory of semiconductors with an impurity band.** *Zhurn. Tekh. Fiz.* **25**: 2050–2060. 1955.

In Russian. Trans. No. 59–18645 available from SLA or LC.

Topics include (1) calculation of the chemical potential of an electron gas in a metal with a narrow band, (2) calculation of electrical conductivity, (3) calculation of the differential thermo emf, (4) the chemical potential of a semiconductor with a narrow impurity band, (5) the electrical conductivity of a semiconductor with an impurity band, and (6) the thermo emf of a semiconductor with a narrow impurity band.

291. SASAKI, KAZUO and NAGAURA, SHIGEO. **Electromotive force change in the thermo cell due to soret effect.** *Chem. Soc. Japan. Bull.* **31**: 498–500, 1958.

The variation of emf of thermo cells with time was investigated. The behaviour of dilute HCl solution agreed with the theoretical derivation of B.

282. SCHOTTKY, W. **Halbleiterprobleme. (Problems of semiconductors).** 381 p., Braunschweig, Verlag Friedr. Vieweg u Sohn, 1958.

A review of this book appears in *Soviet Physics Uspekhi* **2**: 628–629, Jly./Aug. 1959. There are several references to thermoelectricity.

293. SEITZ, FREDERICK. **The modern theory of solids.** 698 p., figs., New York, McGraw Hill, 1940.

Thermoelectric effects and the Hall effect in semiconductors, p. 191–194.

294. SHOCKLEY, WILLIAM. **Theory of transmitted phonon drag.** *In* International Conference on Structure and Properties of Thin Films, Bolton Landing, N.Y. Proceedings, p. 306–327, New York, Wiley, 1959.

Application of the theory to thermoelectric power is discussed, p. 311–312.

295. SHTENBECK, M. **An attempt to determine an increase of the charge carrier temperature caused by an electric field in germanium.** *Izvest. Akad. Nauk. SSSR. Ser. Fiz.* **20**: 1560–1562, 1956.

In Russian.

Non-uniform c.d. distribution in a semiconductor causes the appearance of a special type of thermoelectric emf, U, which was measured by means of probes on specially cut Ge. It can be calculated, that in order to raise the temperature of the electron gas by 1° at room temperature, an increase of the electric field of 4–6 V/cm. is required. An increase of the same order of magnitude can be theoretically derived.

296. SIEGEL, ERNST. **Ueber den einfluss des druckes auf die stellung fluessiger metalle in der thermoelektrischen spannungsreihe. (The effect of pressure on the position of liquid metals in the sequence of thermoelectric voltage).** *Ann. Physik.* **38**: 588–636, 1912.

In German.

This investigation extends the temperature range to 400° in order to determine the effect on liquid Bi and Sn, but this demanded the low-pressure range of only 50 kg./cm^2.

297. SKORIKOV, S. V., ASKENAZI, A. I. and DEKHTYAR, M. V. **Method of sorting steels based on signs of thermoelectric effect.** *Zavodskaya Lab.* **11**: 95–98, 1945.

In Russian.

Translation available from Henry Brutcher, Trans. 2767, 9 p.

Describes development of a routine method for sorting of steel, based on the sign (not the magnitude) of thermoelectric force.

298. SMITH, F. G. **Pyrite geo-thermometer.** *Econ. Geol.* **42**: 515–523, Sept. 1947.

A relation between the thermoelectric potential of electronically conducting crystals and the temperature at which they are formed is deducted, certain conditions remaining similar. A device for measuring the thermoelectric potential of pyrite against a metal and the empirical relation of the potential to the temperature of formation is described.

299. SMIT, J. **The influence of elastic shear strains on the conductivity and thermoelectric force of cubic metals.** *Physica* **18**: 587–596, figs., Aug./Sept. 1952.

Elastic shear strains cause a change in the shape of the Fermi Surface of metals. The influence that such a change has upon the electrical conductivity and the thermo-emf has been calculated for monovalent f.c.c. metals, and the results of it have been compared with the experimental values for Cu, Ag and Au. The conclusion can be drawn that the Fermi surface of gold touches the Brillouin zone boundary, whereas that of copper does not, while silver is an intermediate case. The theoretical results account also qualitatively for the experimental values of the trivalent Al.

Also in Philips Gloeilanepenfabrieken. Paper 2060, 10 p.

300. SMOLUCHOWSK, R. **Statistical theory of properties of solid solutions.** *Phys. Rev.* **84**: 511–518, Nov. 1, 1951.

Properties of binary solid solutions are considered from the point of view of the fluctuation of local composition in the crystalline lattice. These variations influence the properties of the alloys by varying the corresponding local concentration of electrons. A simple general statistical method is given for calculating properties of random and ordered solid solutions. The theory is applied to saturation magnetization, temperature coefficient of electrical resistivity, thermoelectric power, and other properties of various alloys.

301. SOCHARD, I. I. and BECKER, J. H. **Measurement of thermal diffusivity in semiconductors: InSb and Mg_2Sn.** *Am. Phys. Soc. Bull.* **4**: 134, Mar. 30, 1959.

Abstract only.

"Accurate measurements of thermal diffusivity k in metals have been made from analysis of temperature waves due to periodically heating one end of an effectively semi-infinite rod. Generally low-frequency heat pulses (f~1/100 cps) and large samples (~25 cm long) are employed. In contrast, with smaller semiconductor samples (~0·5 x 1 x 10 mm) we use higher frequency heat pulses (f~10–1000 cps) obtained by chopping light which is strongly absorbed at a large area surface of the specimen; temperature waves are deduced from thermoelectric power, Nernst, or bolometric steady-state voltages produced by the sample. Sandblasting reduces undesired photosignals. To calculate k from the bolometric and Nernst effects the ambipolar diffusion constant is required with thermoelectric power voltages V k is obtained from the slope of log V (f) 1/2 vs. (f) 1/2. Results on intrinsic samples at 300 and 400°K agree with calculations from known thermal constants, however, for InSb and anomalous nonlinearity appears when measuring the magneic field dependence of the Nernst effect." Entire item quoted.

302. SOMMERFELD, A. and BETHE, H. **[Electronic theory of metals.] II. Electrons in the periodic potential field.** *In* Handbuch der Physik, 2nd ed., v. 34 (Pt. 2) p. 499–579, Berlin, 1933.

In German. Trans No. 59–10887 available from Translation Center, Special Libraries Association, Crerar Library, Chicago, Ill.

Sections translated are: (d) Electrical conductivity interaction of the electrons with lattice vibrations, and (e) More complicated effects. In d are considered preliminary ideas, Bloch's theory (assumption of thermal equilibrium of the lattice waves), Peierls' "Umklapp processes," and supplements to the theory. Under e are discussed galvanomagnetic effects, and thermoelectric effects. A section (e. c) on radiation effects is not included.

303. STEELE, M. C. and DELAUNAY, J. **Empirical correlation for a thermoelectric property of superconductors.** *Phys. Rev.* **82**: 276–277, Apr. 1951.

Letter. It is pointed out that E_0O^2/T_c^2 has approximately the same value for Pb, In, Sn and Tl. Here O is the Debye temperature and E_0 is the emf in a thermoelectric circuit, part of which is superconducting and part made normal by means of suitably applied magnetic fields, the two junctions being at $T=0$ and $T=T_c$ (the normal transition temperature).

304. STEELE, M. C. and BABISKIN, J. **Magneto-thermoelectric behavior of bismuth at liquid helium temperatures.** *Phys. Rev.* **94**: 1394–1395, June 1, 1954.

Letter. The thermoelectric voltage across a Bi crystal at 4·38°K in the direction of the trigonal axis shows oscillations as a function of a magnetic field applied perpendicularly. The oscillations were of constant period in 1/H, and this period agreed well with the corresponding period for the de Haas–van Alphen effect.

305. STEELE, M. C. **Thermoelectromotive force of a superconductor versus the same metal in the non-superconductive state.** *Phys. Rev.* **81**: 262–267, Jan. 1951.

Measurements have been made for Pb, Sn, In and Tl. The technique used differed in several respects from that employed by previous workers. Results are discussed in light of existing theory. It is found that the data obtained are in good agreement with a relation derived from Fermi-Dirac statistics and the assumption that the Thomson coefficient of a superconductor is zero.

306. STIL'BANS, L. S. **On the commutation of semiconductor thermoelements.** *Zhurn. Tekh. Fiz.* **27**: 212–213, Jan. 1957.

In Russian.

Translation in Infosearch Tech. Lt. Info. Serv. Russian Lit. Survey SEM–2–**57**: 3.1–3.2, 1957.

Concerns the problem of coating thermoelements so that they can be joined with a bridge made of any metal.

307. STRUG, E. M. and PANCHENKO, E. V. **Structural and constitutional investigation of alloys using the micro-thermoelectric method.** *Nauch. Dok. Vys. Shkoly. Met. No.* **2**: 252–255, 1959.

In Russian.

Method based on measurements of the thermo-emf.

308. SUCHIL'NIKOV, S. I. **Thermoelectric properties of steel slags.** *Fiz.-Khim. Osnovy Prolzvodstva Stali. Akad. Nauk. SSSR. Inst. Met. im. A. A. Baikova. Trudy* 3 *ei Konf.* 1955, p. 453–463, 1957.

For English abstracts see *Chem. Abs.* **54**: 6326, Apr. 10, 1960.

309. TARABA, F. R. and PAINE, S. H. **Effect of neutron irradiation on the thermoelectric emf and electrical resistivity of metals and alloys.** *In* Argonne National Laboratory. Annual Report for 1958, p. 109–119, Lemont, Ill., Mar. 1959.

Includes a schematic diagram of a thermoelectric circuit used to measure average thermoelectric power.

310. TAUBER, G. E. **A generalized variationa principle for transport phenomena.** *Can. J. Phys.* **36**: 1308–1318, 1958.

A generalized variational principle was formulated which takes the phonon distribution functions and the external magnetic field into account, is valid for an arbitrary direction of the electric field and polarization of the lattice vibrations, and does not depend on any special form of the energy surfaces. The various transport coefficient, for both thermoelectric and thermomagnetic phenomena, are obtained by the Ritz method in terms of infinite determinants without requiring an explicit solution of the transport equations.

311. TEMPLETON, I. M. **A superconducting reversing switch.** *J. Sci. Instr.* **32**: 172–173, illus., May 1955.

A reversing switch is described in which either of two pairs of tantalum wire elements may be brought into the normal (resistive) state by energizing miniature electromagnetic circuits. Some measurements of small thermal electromotive forces are given in illustration of the performance of the switch.

312. TIPPLE, P. M. and HENISCH, H. K. **Thermal effects at point-contact diodes.** *Phys. Soc. Proc.* **66B** 826–832, Oct. 1, 1953.

Measurements were made on a 4·2−Ω cm. n-type and on 12−Ω mc. p-type Ge illuminated with white light. Au or Ag rectifying electrodes were used. The results found for the floating potential, the contact capacitance and the derived current/voltage barrier characteristic are given and compared with those derived from theory.

313. TOLMAN, R. C. and FINE, P. C. **On the irreversible production of entropy.** *Rev. Mod. Phys.* **20**: 51-77, Jan. 1948.

Equations for the first and second laws of thermodynamics as applied to any system are obtained in general terms. These are applicable where, in addition to the changes occurring in the system due to heat transfers and the performance of work, energy or entropy changes also occur due to mass transfers. The first and second law equations are directly applied to the problems of viscous flow and the thermoelectric effect. The latter application, whereby the usual relationships for the Peltier and Thomson coefficients are deduced, avoids the difficulties of many more familiar treatments.

314. TROUSIL, ZDENEK. **Anomalous thermal electromotive force with germanium.** *Czechoslov. J. Phys.* **6**: 170–172, 1956.

In English.

The occurrence of a thermo-emf in a semiconductor was predicted by Tauc, if at some point in the semiconductor conditions exist for a non-equilibrium concentration of current carriers. In Ge, such conditions exist when there is a considerable temperature difference over distances of less than 1 mm. Describes experiments on Ge strip between 0 and 100°. There is a minimum (or a maximum, respectively) emf at 40°. The results are discussed theoretically.

315. TSUJI, MIKIO. **Transport phenomena in monovalent metals.** *Kyushu Univ. Mem. Fac. Sci.* **2B**: 119–128, 1958.

"Solutions which are nearly valid at all temperatures and for any impurity concentration, including the case of ideally pure metals, are obtained by solving the Boltzmann equations for electrons and phonons by a modified variational method. The general spherical energy-band model, a good approximation for alkali metals even at low temperature, and possibly for all monovalent metals at high temperatures is assumed. Umklapp processes were disregarded. The results for electrical and thermal conductivity agree with those of Hanna and Sondheimer. Their results for the thermoelectric power are valid only for certain special cases. The method gives results identical with those obtained by Dorn, and is more convenient in many cases." *Met. Abs.* **26**: 588, Apr. 1959.

316. VERSCHAFFELT, J. E. **The electrodynamic potential.** *Acad. Roy. Belg. Bull. Glasse. Sic.* **38**: 593–606, 1952.

In French.

Gives a fuller discussion of the idea of an electrodynamic potential and applies it to the Volta and Thomson effects, eddy current effects and to the various magnetoelectric and thermomagnetic effects.

317. WAGENBRETH, HELMUT. **The Benedicks [thermoelectric] effect in mercury.** *Ann. Physik.* **19**: 166–168, 1956.

In German.

It has been suggested that the Benedicks effect depends on the presence of grain boundaries, but experiments on single crystals are lacking. The author used highly purified liquid Hg, since liquid metal is even more homogeneous than a single crystal. Contrary to results of Benedick and Sederholm (1938) no thermo-emf was found.

318. WAGNER, ERNST. **Ueber den einfluss des hydrostatischen druckes auf die stellung der metalle in der thermoelektrischen spannungsreihe. (The effect of hydrostatic pressure on the position of metals in the sequence of thermoelectric voltage).** *Ann. Physik.* **27**: 995–1001, 1908.

In German.

Reports investigations on fifteen metals and several alloys between 0° and 100° and up to 300 kg/cm² pressure. Effects were linear in this range.

For solids the magnitude of the effect is much smaller than for liquid mercury, and is roughly of the order of 5 x 10^{-12} volts per degree C. per kg/cm².

319. WIRTZ, K. **Thermal diffusion and heat of transfer in condensed phases.** *Z. Physik.* **124**: 482–500, 1948.

In German.

The important quantity determining thermal diffusion and thermal-diffusion potentials (homogeneous thermoelectric effect) is the "heat of transfer," Q*, the net energy carried by one mole of the diffusing substance. The material flow may be either up or down the temperature gradient, depending on whether Q* is positive or negative. The Soret coefficient (fractional change in concentration per degree temperature difference) is $-Q^*/RT^2$.

320. WOOLEY, R. L. **Thermoelectric power and the Bauschinger effect.** *Nature* **174**: 566–567, Sept. 18, 1954.

Letter. It is suggested, and verified experimentally for copper, that thermoelectric power should remain approximately constant during Bauschinger straining (a reversal of stress after plastic deformation).

321. YOVANOVITCH, J. **Inhibition by prior thermoelectric treatment of the colorations developed in pure fused silica by irradiation, particularly by neutrons.** *J. Phys. et Radium.* **18**: 640–641, 1957.

The 2420-A band of quartz disappears on heating in an oxidising atmosphere at about 1150°. Samples of vitreous silica subjected to thermoelectric treatment did not colour in the visible spectrum after irradiation with $1{\cdot}6 \times 10^{18}$ neutrons /sq. cm.

322. ZAREMBO, L. K., KRASIL'NIKOV, V. A. and SHKLOVSKAYA-KORDI, V. V. **Propagation of ultrasonic waves of finite amplitude in liquids.** *Akust. Zhurn.* **3**: 29–36, 1957.

In Russian.

Thermoelectric measurements were made at 15· Mc/s for various liquids of the variation of absorption with intensity. Liquids with a low absorption coefficient at low intensities were found to have absorptions two orders higher at 4 W/cm^2. The absorption coefficient was found to vary linearly with the amplitude of the acoustic pressure. Under high static pressure increase of the absorption coefficient is limited by cavitation.

323. ZIL'BERMAN, G. E. **Oscillation effects in a magnetic field.** *Akad. Nauk. SSSR. Ser. Fiz. Izvest.* **19**: 404–408, 1955.

In Russian.

The theories of the dispersion of electrons in a magnetic field are reviewed and it is shown that oscillations of the magnetic susceptibility, of the thermal conductivity in a magnetic field, of resistivity, Hall effect, and thermal emf can be calculated on the basis of a quadratic law of electron dispersion.

324. ABELES, FLORIN. **Resistance electrique et pouvoir thermoelectrique supplementaires dux aux lacunes dans les metaux. (Increased electrical resistance and thermoelectric power due to holes in metals).** *Acad. Sci. Paris. Compt. Rend.* **237**: 796–798, Oct. 12, 1953.

In French.

The changes of resistance and thermoelectric power due to lattice defects are evaluated in terms of electron moments and impurity concentrations, using a simple model according to which the metal consists of an electron gas obeying Fermi-Dirac statistics. Results are compared with experimental values for Ag, Au, and Cu.

325. AGAFONOVA, E. N. **The multielectron model of semiconductors.** *Fiz. metal. i. Metalloved.* **2**: 391–396, 1956.

In Russian. Not examined.

"The current theoretical explanation, based on the single-electron model, for the thermoelectric properties of semiconductors (Ge, Si, etc.) is often unsatisfactory as regards quantitative agreement, although in the majority of instances agreement is quite satisfactory despite the complete disregard of the effect of interaction between electrons. This paper gives a quantum-mech. derivation, based on the multielectron model, for the thermoelectric behaviour of pure semiconductors. From the final equation, one may compute the differential thermoelectric force and the coefficients of Peltier and of Thomson; the values so calculated agree with data in the literature, provided only that an energy of the order of 10^{-13} ergs is assumed as characteristic for the transition of electrons from one 'node' of the lattice to a neighbouring 'node'." (*Chem. Abs.* **51**: 4238, 1957).

326. AIRAPETYANTS, S. V. and BRESLER, M. S. **Thermoelectric power and surplus heat conductivity of heterogeneous systems.** *Zhurn. Tekh. Fiz.* **28**: 1935–1938, Sept. 1958.

Translation in Infosearch Ltd.

Russian Lit. Survey SEM-7-59.

327. AIRAPETYANTS, S. V. and BRESLER, M. S. **Termoelektrodvizhutshaya sila i dobavochnaya teploprovodhost' geterogeniikh sistem. (Thermoelectromotive force and the additional heat conductivity of heterogeneous systems).** *Zhurn. Tekh. Fiz.* **28**: 1935–1938, Sept. 1958.

In Russian.

Calculation of thermoelectromotive force coefficient of a polycrystal, increase of polycrystal heat conductivity, provoked by heterogeneity of its thermoelectric properties; and thermoelectromotive force coefficient of matrix system in the case of low concentration of inclusions, and of matrix phase.

328. AIRAPETYANTS, S. V. **Thermoelectromotive force and additional thermal conductivity of a statistical mixture.** *Zhurn. Tekh. Fiz.* **27**: 478–483, 1957.

In Russian. Translation appears in Infosearch Tech. Lit. Info. Serv. Russian Lit. Survey SEM-3-57, p. 2·1–2·7, June 1957.

One of the factors determining the efficiency of thermoelectrical devices is $Z=\alpha^2\sigma/x$, where $\alpha=$ thermoelectric power, $\sigma=$electrical conductivity, and $x=$thermal conductivity. To obtain maximum values of Z, alloys constituting complex psuedobinary systems in solid solution are used which on melting are subject to both liquidation and segregation with the results that thermoelements prepared by pressing powdered alloys of this type are not homogeneous and can be regarded as statistical mixtures in which various phases are randomly distributed in the form of particles of roughly the same size but characterised by different α, σ, and x. Using Odelsevskii's method of calculating the overall mixtures of σ, and x of such mixtures, the author derives a general expression for α of a statistical mixture of an arbitrary number of components, and calculates the increase of the thermal conductivity of such a mixture due to Peltier effect. Values of α calculated for a two-component mixture of PbTe agreed well with the experimental data.

329. ANSELM, A. I. and KLYACHKIN, V. I. **Kinetic processes in atomic semiconductors taking into account scattering of electrons by ions.** *Zhurn. Eksp. Teor. Fiz.* **22**: 297–302, 1952.

In Russian.

The theory, taking account of the mechanism of scattering of current carriers on ionized centres, shows that the total resistivity is not the simple sum (as some authors had assumed it to be) of the lattice resistivity and that due to electron scattering. In the light of the amended theory, formulae are obtained for the thermo-emf and Hall constant. (*Sci. Abs.* **55A**: 8197, 1952).

330. APPEL, J. **Die thermokraft von nicht polaren halbleitern. (Thermoelectric force of non-polar semiconductors).** *Z. Naturforsch.* **12a**: 410–424, May 1957.

In German.

The distribution functions of electrons and thermal lattice-waves are solved simultaneously and self-consistently for non-degenerate isotropic semiconductors. For electrons the elastic interaction with the longitudinal acoustical lattice-vibration and ionized impurity atoms is considered to be the collision process; for the longitudinal thermal lattice-waves the interactions with similar lattice waves, with electrons, and with crystal boundaries are the collision processes. The calculations give values for the thermo-emf, the thermal conductivity, and calculated values are compared with measured values on Ge single crystals. The agreement is very good.

331. APPEL, J. **Phonenen-relaxationzeit und magnetische thermokraft änderung von halbleitern. (Phonon relaxation tim and magnetic change in thermoelectric force in semiconductors).** *Z. Naturforsch.* **14A**: 838–840, Sept. 1959.

In German. Translation available from Associated Electrical Ind. Aldermaston, Berkshire, Eng.

Expressions are given for the differential thermoelectric power of semiconductors with a simple band structure in a strong magnetic field. The decrease of thermoelectric power with increasing field is dismissed.

332. APPEL, J. **Theory of thermoelectric and thermomagnetic effects in nonpolar isotropic semiconductors.** *Phys. & Chem. Solids.* **8**: 353–358, Jan. 1959. (Proc. 1958 Internatl. Conf. on Semiconductors.)

Part I: Introduction to the physical and mathematical problem; Part II: Some results for the thermoelectric and the thermomagnetic effects.

A review of the coupling between phonons and electrons and its effect on thermoelectric and thermomagnetic properties in semiconductors.

Paper with same title in *Z. Naturforsch.* **13a**: 386–402, May, 1958. (See Item 630, May 1959 issue).

333 APPEL, J. **Theory of the thermomagnetic effects of nonpolar isotropic semiconductors.** *Z. Naturforsch.* **13a**: 386–402, May 1958.

In German.

The author's previous theory for the simultaneous derivation of the distribution functions of electrons and phonons (acoustic), from the two coupled Boltzmann equations, is extended to include the effect of an applied magnetic field. Besides the mutual scattering of electrons and phonons by one another, the scattering of the former by impurities and the latter by grain boundaries and other phonons is considered. The following isothermal and adiabatic effects are calculated as functions of the magnetic field strength and temperature: the variation of thermoelectric power and thermal conductivity with transverse magnetic field and the Ettingshausen-Nernst effect. Explicit results are given for weak and strong fields while computed results, at intermediate fields, for various values of the scattering parameters, are presented in the form of graphs. The field dependent thermoelectric power of p-type germanium, measured at 80°K, is in good agreement with the calculated result. (*Phys. Abs.* **62**: 3452, 1959).

334. AVAK'YANTS, G. M. **On the letter to the editor by I. M. Tsidil'kovskii and F. G. Bass.** *Zhurn. Eksp. i Teor. Fiz.* **30**: 806, Mar. 1956.

In Russian.

A rebuttal of the criticism by Tsidil'kovskii and Bass of the author's papers. The author maintains the validity of his analysis of thermoelectric and, galvano-, thermo-, and photomagnetic effects in semiconductors subjected to strong electric fields.

335. BARANSKII, P. I. and KONOPLYASOVA, N. S. **Izuchenie ob'emho-gradientnoi termoeds i teploprobodnosti v monokristallakh germaniya izvestnoi kristallograficheskoi orientatsii. (Study of volume-gradient thermo-emf and heat conductivity in germanium single crystals with definite crystallographic orientation).** *Zhurn. Tekh. Fiz.* **28**: 1621-1630, Aug. 1958.

In Russian.

The paper describes a method for studying the volume-gradient thermal emf which is developed at volume inhomogeneities of a semiconductor (germanium). An analysis is made of the temperature variation of this thermal emf; it is shown that it vanishes in the region of intrinsic conductivity where the nonuniformity in the distribution of residual impurities no longer produces an appreciable distortion of the homogeneity of the specimen. For this case the homogeneity of the specimen is established due to the sharp increase in conductivity caused by interzonal thermal transitions. At the same time the isotropic nature of the thermal emf and the thermal conductivity in germanium is verified.

336. BARANSKII, P. I. **Mobility of minority current carriers in colinear electric and thermal fields.** *Zhurn. Tekh. Fiz.* **28**: 694–703, Apr. 1958.

In Russian.

Using the zero method of measuring the drift mobility of minority carriers in n-type germanium in the presence of temperature gradients, it is shown that there is no appreciable entrainment effect (electron-background interaction) in the range of room temperatures. The negative reply obtained to the question of the electron-background interaction excludes the explanation based on the entrainment effect, for the incompatibility of the fundamental thermoelectric relations following from the first and second laws of the thermodynamics of reversible processes.

337. BARANSKII, P. I. and KOMUKHAYEV, E. I. **Volume-gradient emf in the presence of current in germanium.** *Zhurn. Tekh. Fiz.* **28**: 1896–1904, Sept. 1958.

In Russian.

Experimental proof is given of the appearance of volume-gradient emf in the presence of current in germanium. The correlation of variations of the volume-gradient emf and of p to the coordinate was established. It was shown that the volume-gradient emf in n- and p- type germanium have opposite signs. Attention is drawn to the fact that in the case of semiconducting materials a very high accuracy in measuring the electric characteristics (by means of a probe method) cannot be reached if the volume-gradient emf is ignored.

338. BARANSKII, P. I. **The volume Peltier effect in germanium.** *Zhurn. Tekh. Fiz.* **28**: 225–230, Feb. 1958.

In Russian. Translation in *Soviet Phys. Tekh. Phys.* **2**: 201–205, Feb. 1958.

The volume Peltier effect is expected to be present in a semiconductor with non-uniform resistivity; it consists of the absorption or generation of heat when a d.c., I, is passed through the material. The experimental arrangement used to detect the effect in Ge single-crystal specimens is described; six specimens with average resistivities of 0·018–0·61 cm. were studied. The results show that the effect αI as expected. If there is a volume Peltier effect, there should also be a gradient of thermo-emf; the apparatus used to detect this effect is also described.

339. BARRIE, R. **Influence of exchange and correlation on electron transport in metals.** *Phys. Rev.* **103**: 1581, Sept. 1, 1956.

Various errors are pointed out in Blatt's calculation of the change produced in the conductivity and thermoelectric power of metals when one uses the Bohm and Pines ε-k curve instead of the usual standard parabolic curve. The correct results are derived.

340. BENEDICT, R. P. **Thermoelectric effects.** *Elec. Mfg.* **65**: 103–118, illus., Feb. 1960.

An introduction to thermoelectric theory is provided. The first section concerns the historical sequence of developments from Seebeck's basic discovery of thermoelectric effects to the famous Kelvin relations in 1854. In the next section, thermoelectricity is discussed from the microscopic (free-electron) and macroscopic (irreversible thermodynamic) points of view. Finally, the four basic applications of thermoelectric phenomena (power generation, heating, cooling, and temperature sensing) are considered. The various circuits, means for judging their performance, and graphical and numerical results are given.

A bibliography in which early historical references are cited is appended.

341. BLATT, F. J. **Effect of point imperfections on the electrical properties of copper. II. thermoelectric power.** *Phys. Rev.* **100**: 666–700, Oct. 15, 1955.

Theoretical treatment of the influence of Frenkel defects; due to a small concentration of As, on the absolute thermoelectric power of Cu; general remarks on the use of thermocouples in a radiation field.

342. BLATT, F. J. **Residual resistivity of copper and silver alloys: dependence on periodic table.** *Phys. Rev.* **108**: 285–290, Oct. 15, 1957.

Attention is called to the fact that polyvalent impurities of the silver period of the periodic table give rise to a smaller residual resistivity in both copper and silver than do polyvalent impurities belonging to the copper period. An explanation of this experimental result is presented. The explanation is based on a modification of the Friedel sum rule suggested by Harrison by which one may take lattice distortion into account. The calculations reflect in every detail the qualitative features of the experimental data, and moreover, lead to better quantitative agreement between theory and experiment than previous calculations based on the free-electron models. The occurrence of a similar period dependence of the thermoelectric power of these alloy systems is suggested.

343. BLEANEY, B. I. and BLEANEY, B. **Electricity and magnetism.** 676 p., illus., Oxford, Clarendon Press, 1957.

Thermoelectric effect, p. 94–99.

344. BONIFAS, H. **A study of some problems in electrostatics.** *Rev. Gén. Elec.* **64**: 149–158, Mar. 1955.

In French.

An interpretation of the electrostatic behaviour of conducting materials is given in terms of some conceptions of the electronic theory of solids. The Peltier effect and contact potential are also discussed.

345. BORELIUS, G., KEESOM, W. H., JOHANSSON, C. H. and LINDE, J. O. **Establishment of an absolute scale for the thermoelectric force.** *Ned. Akad. Wetens. Proc.* **25**: 10–14, 1932.

The authors introduce a formula which indicates the thermoelectric force per degree of metal in the absolute thermoelectric scale. They calculate this quantity for tin, lead and the silveralloy-normal they used, on the basis of their measurements of the thermoelectric forces and of the Thomson-heat, of the assumption that $\sigma=0$ in the superconducting state, and of an interpolation for tin between 7·2 and 20 K.

346. BOTTGER, OTTO. **Ueber die leistungsgrenzen der thermoelektrischen effekte bei halbleitern. (Efficiency limits of the thermoelectric effects of semiconductors).** *Z. Physik.* **151**: 296–306, illus., 1958.

In German.

The efficiency of a loaded thermocouple and the maximum reduction in temperature of a Peltier couple are calculated. A non-dimensional magnitude—the thermo metal coefficient enables the quality of a combination to be assessed.

Joint Publications Research Service Translation is available.

347. BRUZS, B. **Zur theorie der thermoelektrizität. (Theory of Thermoelectricity).** *Z. Elektrochem.* **28**: 777–779, 1932.

In German.

Added the Seebeck and Peltier effects to the theories of thermoelectricity.

348. California University. Radiation Laboratory, Livermore, Calif. **Thermodynamics of irreversible processes: the experimental verification of the Onsager reciprocal relations,** by D. G. MILLER, 81 p., Jly. 30, 1959. (Rept. 5644-T) (Contract W7405-eng-48).

In the last twenty years a thermodynamic theory of irreversible processes (TIP) has been vigorously developed which has been able to treat irreversible phenomena in a detailed way. The present macroscopic form of the theory was

suggested primarily by the statistical mechanical investigations of Onsager. The presently available experimental data are collected for a variety of quite different irreversible phenomena and it is shown that this evidence does indeed verify the Onsager Reciprocal Relations. Thermoelectricity, electrokinetics, transference in electrolytic solutions, isothermal diffusion, heat diffusion, heat conduction in anisotropic solids, and thermogalvanomagnetic effects are the phenomena considered in detail. (*Nuclear Sci. Abs.* **14**: 3865, Feb. 29, 1960).

349. CALLEN, H. B. **The application of Onsager's reciprocal relations to thermoelectric, thermomagnetic and galvanomagnetic effects.** *Phys. Rev.* **73**: 1349–1358, June 1, 1948.

Analysis of the effects by means of the reciprocal relations leads to a simple and intuitive interpretation of the thermoelectric effects, provides a valid derivation of the Kelvin relations, and answers the long-standing question as to the existence of relations among the effects in a magnetic field. There exist two independent relations among the 8 commonly defined coefficients in a magnetic field—one of these relations having been previously given by Bridgman. The nature of the second relation is discussed. Also, certain general observations on the applicability of the Onsager relations to steady-state processes are discussed.

350. Carnegie Institute of Technology, Atlanta, Ga. **Transient and steady state theory of semiconductor thermoelectric cooling cells,** by N. ALFONSO. 114 p., Nov. 1959. (Contract Nonr.-760(09).)

Thermoelectric phenomena are reviewed on the basis of the band theory of a non-degenerate semiconductor and the steady-state operation of a thermoelectric cooling cell is presented as a starting point for the study of the transient behaviour.

The transient equations are developed for the cell assuming uniform temperature within the insulated chamber for elements of known thermal inertia, and assuming a hot junction temperature that is constant at the ambient value. These equations are investigated by Paplace transformation methods for turnoff and turn-on step-function currents and the influence of the physical and geometric parameters of the system is examined. The cross-sectional area to length ratio of the thermoelements and the heat load are shown to be important in determining transient response and under certain conditions temperature overshoot may be expected.

Repetitive pulse conditions are studied and also the effect of sinusoidal ripple present in the power supply on the mean temperature drop. The ripple reduces the temperature drop available but with suitable circuit proportions the effect may be reduced.

351. CEZAIRLIYAN. ARED. **Thermoelectric phenomena—theory and applications.** 129 p., Sept. 1959. Thesis, M. S., Purdue University.

Fundamental concepts of thermoelectric phenomena are studied with emphasis on the various thermoelectric effects. A fairly complete review of published information on this subject is given.

352. CHAMBERS, R. G. **The two-band effect in conduction.** *Phys. Soc. Proc.* **65A**: 903–910, Nov. 1952.

For an isotropic two-band conductor in a transverse magnetic field, the various galvanomagnetic, thermomagnetic and thermoelectric coefficients are derived by elementary arguments in terms of those of the individual bands. The expressions are applicable to quasi-free electrons of any degree of degeneracy; for fully degenerate electrons they reduce to those given by Sondheimer and Wilson. When the square of the thermoelectric power is comparable with the Lorenz number, as may happen in semiconductors, the expressions for the adiabatic thermomagnetic and thermoelectric effects become extremely complicated, though those for the isothermal effects remain reasonably simple.

353. CHANU, JACQUES. **The stationary thermoelectric potential in ionic solutions in Soret equilibrium.** *Acad. Sci. Paris. Compt. Rend.* **243**: 239–241, Jly, 16, 1956.

In French.

The application of the thermodynamics of irreversible processes, based on the reciprocal relations of Onsager, to the study of thermal diffusion in ionic solutions, leads to phenomenological relations on the existence of an electrical potential gradient which appears with the gradients of concentration and of temperature. Comparison is made with the author's experimental results.

354. CHASMAR, R. P. and STRATTON, R. **The thermoelectric figure of merit and its relation to thermoelectric generators.** *J. Electron & Contr.* **7**: 52–72, figs., Jly. 1959.

The expression for the figure of merit of a semiconductor of given carrier mobility and lattice thermal conductivity expressed in terms of generalised Fermi-Dirac functions has been numerically evaluated for various scattering indices. The results are presented graphically enabling the maximum figure of merit to be found. High-temperature limitations due to minority carrier production are considered in relation to the energy gap of the semiconductor. The results are discussed in connection with bismuth telluride and other sulphides, selenides and tellurides of the heavy metals.

355. DE GROOT, S. R. **Thermodynamics of irreversible processes (with appendix on hydrodynamics and thermodynamics).** 44 p., figs., College Park, University of Maryland, 1951. (University of Maryland, Institute for Fluid Dynamics and Applied Mathematics. Lecture Ser. 13).

Thermoelectricity, p. 11–15.

356. DINGLE, R. B. **The concept of formal relaxation times in the theory of electronic conductors at low temperatures.** *Physica*, **22**: 698–700, 1956.

The electrical conductivity, thermal conductivity and thermoelectric effects in metals and polar semiconductors can be expressed by formulae which are natural extensions of the elementary theory valid for those circumstances for which a "universal" relaxation time can be defined.

357. DOMENICALI, C. A. **Irreversible thermodynamics of thermoelectric effects of inhomogeneous anisotropic media.** *Phys. Rev.* **92**: 877–881, Nov. 15, 1953.

Beginning with the isotropic form of the thermoelectric equations of Onsgaer's irreversible thermodynamics as treated by Callen and de Groot, a direct transcription is made to the case of inhomogeneous and anisotropic media. The emf of Kelvin, Bridgman, Ehrenfest and Rutgers is the gradient of the electrochemical potential and a general formula is given for this gradient in anisotropic media.

358. DOMENICALI, C. A. **Irreversible thermodynamics of thermoelectricity.** *Rev. Mod. Phys.* **26**: 237–275, Apr. 1954.

A detailed treatment, using the Onsager reciprocity relations, based upon electrochemical potentials. The first part deals with isotropic media; the treatment is later extended to anisotropic media. Comparison is made with the methods of Kelvin, Bridgman, Ehrenfest and Rutgers, Kohler, Meixner, and Meissner. Appendices deal in some detail with applications of the theory to particular systems and connections with experimental results.

359. DOMENICALI, C. A. **Stationary temperature distribution in an electrically heated conductor.** *J. Appl. Phys.* **25**: 1310–1311, Oct. 1954.

The thermodynamic theory of irreversible processes as developed by Onsager, de Groot, and Callen is used to derive in a straightforward way the partial differential equation for the stationary temperature distribution in an electrically heated, chemically inhomogeneous conductor. It is shown that the form of this differential equation given in 1900 by Diesselhorst (for homogeneous media) in terms of the electrical potential gradient, is incorrect.

360. DOMENICALI, C. A. and OTTER, F. A. **Thermoelectric power and electrical resistivity of dilute alloys of silicon in copper, nickel, and iron.** *J. Appl. Phys.* **26**: 377–380, Apr. 1955.

Data on the TE power and resistivity of dilute Cu-Si, Ni-Si, and Fe-Si alloys from –195 to 500°C. The Cu-Si emf first decreases with increasing Si, and then again increases, the minimum being at 2 or 3 at. % Si, depending on temperature. The Cu-Si resistivity is typical of Cu-base alloys, increasing per at. % Si, changing from 7·2 microhm cm. at -190°C. to 817 at 840°C. The TE power and resistivity curves for Ni-Si show a characteristic nick at the Curie temperature of each alloy. The Fe-Si TE powers are positive at lower temperatures and become negative at a temperature T. that decreases with increasing Si content. Furthermore, T changes from about 300°C. for pure Fe to about 70°C. for 2 at % Si. The resistivity of Fe-Si alloys increases faster than linearly with temp. as is also the case for Ni-Si alloys below the Curie temperature. Above the Curie point, the Ni-Si resistivities vary linearly with temperature. The increase in resistivity per at. % Si in Fe is 10·5 Microhm cm. at all temperatures within the measured range.

361. DOMENICALI, C. A. and OTTER, F. A. **Thermoelectric power and electron scattering in metal alloys.** *Phys. Rev.* **95**: 1134–1144, Sept. 1, 1954.

TE power depends on how current carriers are scattered by the various deviations of the crystal from a perfect lattice. A semi-empirical theory of TE power in metal alloys, based on a formula of Mott and others, is described.

362. DOMENICALI, C. A. **Thermoelectricity and resistivity in metal alloys at low temperatures.** *Phys. Rev.* **117**: 984–992, Feb. 15, 1960.

Low-temperature behaviour of resistivity and thermoelectric power of metal alloys is explained on the basis of a simple model of "resonance scattering" of conduction electrons by impurity atoms.

363. DOMENICALI, C. A. **Thermoelectric power and electron scattering in metal alloys.** *Phys. Rev.* **112**: 1863–1876, Dec. 15, 1958.

A phenomenological theory is presented for thermoelectric power in binary, ternary, and more complex noble metal-base metal alloys based on the amended Mott formula. In Cr, Mn, Fe, Co, and Ni solutes in Cu, the cross section depends on electron energy as in the slow-electron scatter from vapor-state atoms. The analogy is used to predict ternary and more complex behaviour from binary-alloy data. Experiments are described on Fe, Co, Bi, Si, Ge, Sn, Ga, Au, Sb, Cr, Mn, Pd and Pt in Cu. Cu-Ni-Co, Cu-Ni-Au, and Cu-Ni-Fe alloys are compared to Cu-Ni alloys; the results accord with the theory. The effect of Fe and Co solutes on Cu and Au thermoelectric power are studied.

Article with same title in *Phys. Rev.* **95**: 1135–1144, Sept. 1, 1954.

364. DONAHOE, F. J. **Thermoelectric material requirements.** *In* Papers Presented at Symposium on Solid State and Plasma Physics, p. VII-1-VII-22, Baltimore, Md., Johns Hopkins University, Radiation Laboratory, Jan. 1960. (Tech. Rept. Af-73) (Contract AF33(616) 3374).

Considers the thermoelectric device equations; operation under conditions of other than maximum C.O.P.; and the figure of merit.

365. DORN, DIETER. **A generalised variation method for the treatment of transport phenomena in metals and semiconductors.** *Z. Naturforsch.* **12a**: 739–749, 1957.

In German.

"From the Boltzmann equation for the electron and phonon gas it is shown that the rate of entropy production/unit vol. becomes maximal in transport processes when certain conditions are fulfilled. This principle can be used to calc. approximate values of elec. and thermal transport quantities. The Kelvin relations of thermoelectricity are obtained quite generally. In the case of the isotropic semiconductor with single-band conduction it follows that the Debye temp. plays only a subordinate role. The variation method is used to calc. the thermal and elec. cond. in a simple example." *Chem. Abs.* **52**: 8746, June 10, 1958.

366. DRABBLE, J. R. **Galvanomagnetic effects in p-type bismuth telluride.** *Phys. Soc. Proc.* **72**: 380–390, Sept. 1958.

A satisfactory explanation of the anisotropy of the galvanomagnetic effects in Bi_2Te_3 is one in which the band associated with the transport properties is of the many-valley type. The resistivity components, Hall coefficient, and low-field magnetoresistance coefficient measured on a number of single-crystal specimens at 77°K are consistent with this idea. The variation of the resistivities and the Hall coefficient with temperature between 77° and 290°K is discussed, and the mobility obtained for holes for current flow || the cleavage planes.

367. DRABBLE, J. R. **The effect of strain on the thermoelectric properties of a many-valley semiconductor.** *J. Electron & Control.* **5**: 362–372, Oct. 1958.

The electrical conductivity and thermoelectric power of a many-valley semiconductor are considered as functions of strain, neglecting all effects other than those due to carrier transfer between valleys. For non-degenerate materials, a general treatment is given and it is shown that the absence of other effects can be checked by the condition that the trace of the conductivity tensor is unaltered by the strain.

368. EHRENBERG, W. **Electric conduction in semiconductors and metals.** 389 p., figs., Oxford, Clarendon Press, 1958.

Passages relating to thermoelectric power may be found in this introduction to the physics of semiconductors on pages 4, 5, 21, 22, 27, 62, 74, 76, 188, 199.

369. ELLIOTT, R. J. and BANBURY, P. C. **The theory of semiconductors.** *Met. Rev.* **4**: 257-308, 1959.

In this review article, the theory of electrical resistivity and the Hall effect, and thermoelectric power are discussed.

370. EPSTEIN, P. S. **Textbook of thermodynamics.** 406 p., figs., New York, Wiley, 1937.

Thermoelectric potential differences in the classical electron theory, p. 271–273.

Thermoelectric phenomena, p. 361–368.

371. FEN, G. I. **Valentnye poluprovodniki germanii i kremnii. (Valence semiconductors—germanium and silicon).** *Usp. Fiz. Nauk.* 733–779, Apr. 1958.

In Russian.

English translation in Seitz, F. and Turnbull, D, eds., Solid State Physics, New York, Academic Press, 1955. (Vol. I).

Survey of data on the characteristics of germanium and silicon crystals. Includes: evaluation of the semiconductor theory, ideal crystals, pertubation of the crystal lattice, electron distribution, effective mass, properties of crystals, crystal lattice, optical properties and dielectric constant, magnetic properties, effective mass and structure of the energy zone, impurities, crystal lattice flaws, conductivity phenomena, general theory, conductivity and Hall effect, thermoelectromotive force, conductivity in the case of strong fields, low temperature, and high frequency; and problems related to the biased electron distribution.

372. FIESCHI, R. **Thermodynamical theory of galvanomagnetic and thermomagnetic phenomena.** *Nuovo Cimento* **1** (*Suppl.*): 1–47, 2(*Suppl.*): 1168–1170, 1955.

The theory of thermoelectricity is extended to the case in which a magnetic field is present.

373. FLETCHER, J. G. and LARSON, D. C. **Influence of electron interactions on metallic properties.** *Phys. Rev.* **111**: 455–462, 1958.

A calculation based on the Bohm-Pines description of electron interactions shows the effect of interactions on the one-electron energy in metals. Comparison of calculated and experimental values of band width, specific heat, relaxation times, conductivity, thermo-electric power, and diamagnetic susceptibility for the alkali metals shows fair agreement.

374. FREDERIKSE, H. P. R., JOHNSON, V. A. and SCANLON, W. W. **Thermoelectric effects.** *In* Lark-Horovitz, K. and Johnston, V. A., eds. Solid State Physics, vl. 6, p. 114–128, New York, Academic Press, 1959.

A review article covering the Seebeck, Thomson and Peltier effects; significance and measurement of thermoelectric power; temperature above and below ~ 100°K; the thermoelectric generator and refrigeration.

375. FRIEDEL, J. **Some electrical and magnetic properties of metallic solid solutions.** *Can. J. Phys.* **34**: 1190–1210, 1956.

The resistivity, thermoelectric power, and magnetic susceptibility of metallic solid solutions at room temperature are reviewed, and the relation with their electronic structure is emphasised. The special properties of transitional impurities are related to the emptying of the d shells.

376. FRIEDEL, J. **Thermoelectric power of alloys.** *J. Phys. et Radium.* **14**: 561–565, Nov. 1953.

Mott's calculation for the resistivity when polyvalent impurities (e.g., Zn, Ga, Ge) are substituted in monovalent metals such as Cu is extended to determine the thermoelectric power. The order of magnitude and the variation as a function of impurity concentration are in agreement with experimental results. For Al alloys, in order to obtain theoretical results in agreement with observations, it is necessary to assume two overlapping energy bands.

377. GEBALLE, T. H. **The Seebeck effect in germanium.** *Phys. Rev.* **92**: 857, 1957.

Abstract only of paper given at 1953 Spring meeting of the American Physical Society, Schenectady, April 10–11, 1953.

"The Seebeck effect in germanium has been investigated by previous workers. In this investigation, the Seebeck and Hall effects have been measured from liquid hydrogen temperatures to the intrinsic region for a series of n and p type single crystals. It has been shown quite generally that in a thermoelectric circuit the Seebeck voltage per degree Q is equal to the entropy convected through the circuit per unit current. When the usual band scheme is assumed, the entropy convected by unit current is simply $\triangle E_F/T$ plus a term involving kinetic energy transported by electrons. $\triangle E_F$ is the distance of the Fermi level from the band edge. $\triangle E_F$ determined from Seebeck voltage agrees with $\triangle E_F$ determined from Hall voltage in order of magnitude down to about 200°K. As the temperature is lowered still further, the Seebeck voltage becomes increasingly too large, reaching a maximum just above the hydrogen boiling point. It appears that an additional mechanism other than electron transport of entropy must be considered in order to relate the observed data. This is considered in the next paper by C. Herring." Entire item quoted.

378. General Atomic Corp., San Diego, Calif. **Some considerations of the basic physics of thermoelectric effects,** by W. B. TEUSCH. 9 p., May 12, 1959. (Rept. 774).

This discussion of thermoelectric effects was presented as a talk at the Thermoelectricity Conference Washington, D.C., September 3–4, 1958.

379. General Electric Co., Knolls Atomic Power Laboratory, Schenectady, N.Y. **Electron theory of thermoelectric effects,** by W. W. TYLER. 17 p., Sept. 1951. (Rpt. M-WWT-1).

Expressions are derived which permit the rough prediction of changes in calibration of various thermocouples due to neutron damage. Several generalities are proposed regarding these changes.

380. GUREVICH. L. **Thermoelectric properties of conductors.** *Zhurn. Eksp. i Teor. Fiz.* **16**: 193–228, 1946.

In Russian.

Fact that the temperature dependence of the thermo-emf of various metal couples follows no uniform law leads to the assumption of different mechanisms for the TE effect. Theoretical treatment shows this is possible. In the presence of a temperature gradient in a conductor, resulting in a non-equilibrium distribution of states for both the electrons and the lattice vibrations, the deviation from the equilibrium may be brought about by: (1) direct effect of the temperature gradient on the electrons; (2) convection of the electrons by the stream of lattice waves (phonons) created by the temperature gradient. The latter indirect effect, not heretofore considered, and which may be described as asymmetric scattering of the electron stream by lattice vibration aroused by the temperature gradient, is proved to be prevalent in certain temperature intervals, where as elsewhere the first mechanism predominates. The experimental anomalies in the temperature dependence of the thermo-emf can be explained by transition from one mechanism to another. The theory gives, at higher temperatures, a differential TE emf proportional to I/T; at low temperatures, one proportional to T^3. Thermal conductivity is not materially altered by the introduction of the two mechanisms.

381. HAASE, ROLF. **Contribution to the theory of thermoelectricity.** *Z. Naturforsch.* **11a**: 681–684, 1956.

In German.

Mathematical. A phenomenological calculation of the thermoelectric effects was carried out. Thermal and electrical gradients along a bar containing mobile electrons was considered. By using the Onsager reciprocity law, the Seebeck, Peltier and Thomson coefficients were expressed in terms of the thermodynamical properties of electrons.

382. HAASE, ROLF. **Thermocouples. III. Supplementary views.** *Z. Physik. Chem.* **14**: 292–295, 1958.

In German.

In connection with earlier publications, methods for determining all independent transport coefficients for a nonisothermal solution of a binary, completely dissociated electrolyte and the problem of the reference system for the transport phenomena are discussed. The explicit connection of the initial and of the end value of the thermoelectric force of a thermocouple with the Soret coefficient, Hittorf's transport number and the activity coefficient is deduced.

383. HAASE, V. R. **Theory of thermoelectricity.** *Z. Naturforsch.* **11A**: 681–684, Sept. 1956.

In German.

Discusses several relations between TE coefficients which are deduced from thermodynamics. Simple formula relates heat of transfer of electrons to the difference between the thermal conductivity in absence of electric field and the thermal conductivity in the stationary non-equilibrium state

(absence of electric current). As a consequence of the definite positive character of the entropy production, the author determines an upper bound to the value of the heat of transfer, proportional to the thermal conductivity and electric resistance of the metal. Well known derivation of Thomson's classical relations is discussed in a simple case.

384. HAGA, EIJIRO. **On the theory of the thermoelectricity in two-band semiconductors.** *Phys. Soc. Japan J.* **14**: 35–38, Jan. 1959.

In many literatures the thermoelectromotive force of a circuit composed of two different conductors is expressed by an integral of the field along the circuit with two junctions of different temperatures. This definition is not free from ambiguity when we deal with the thermoelectricity of two-band semiconductors. In the present paper a theory of the thermoelectricity of two-band semiconductors is developed with consideration of temperature dependence of the gap energy. The Thomson relations are proved to be satisfied.

385. HAGA, EIJIRO. **Theory of thermoelectric power of ionic crystals. I.** *Phys. Soc. Japan J.* **13**: 1090–1095, Oct. 1958.

A theory of the emf in AgBr is developed, in which the experimental conditions are properly considered. The gradient of the electrochemical potential of silver ions is calculated, since it is related to the quantity measured by the potentiometer, that is the difference between the Fermi levels at two free ends of lead wires. An expression is derived, which is applicable to AgBr mixed with $CdBr_2$ at arbitrary temperatures.

The Peltier and Thomson coefficients in the steady state are independently calculated for this special case, and the result shows that the Kelvin relations are really satisfied in the steady state. Finally, the theory is compared with the experiments of Patrick and Lawson.

386. HAGA, EIJIRO. **Theory of thermoelectric power of ionic crystals. II.** *Phys. Soc. Japan. J.* **14**: 992–996, Aug. 1959.

"A theory of the thermoelectric power of the NaCl crystal doped with $CdCl_2$ is developed, when we measure it by using the chlorine gas electrode. We derive also the expressions of it by taking into account the Coulomb interaction between defects in NaCl and AgBr, and estimate the correction terms to the simple theory. Next the relation between the thermoelectric power with the metallic electrodes and that with the halogen electrodes is derived, and the theoretical result is compared with experiments in silver halides and lead halides."

387. HAGA, EIJIRO. **Theory of thermoelectric power of ionic crystals. III.** *Phys. Soc. Japan. J.* **14**: 1176–1181, Sept. 1959.

When temperature gradient is given in a specimen of AgCl doped with CuCl, its thermoelectric power changes with time owing to the thermal diffusion of copper ions, and then reaches its steady value. If the temperature gradient is removed after such a steady state is attained, the electromotive force continues to exist for a while, but it decreases with time according as the copper ions diffuse again to the previous homogeneous distribution. The expressions for such processes are derived under proper assumptions. The time constant for them is estimated with use of the conductivity data of Ebert and Teltow. The information on the heat of transport of Cu% will be obtained if experiments on such processes are carried out.

388. HANNA, I. I. and SONDHEIMER, E. H. **Electron and lattice conduction in metals.** *Roy. Soc. London. Proc.* **239(A)**: 247–266, Feb. 26, 1957.

Theory of the transport phenomena; transport equations; electrical and thermal conductivity; thermoelectric power.

389. HASHIMOTO, KIMIO. **Integrals in the thermoelectric power of semiconductors.** *Kyushu Univ. Mem. Fac. Sci. Ser. B* **2**: 165–170, Dec. 1958.

A general formula is presented for the thermoelectric power Q of non-polar and isotropic semiconductors.

390. HATSOPOULOS, G. N. and KEENAN, J. H. **Analysis of the thermoelectric effects by methods of irreversible thermodynamics.** *J. Appl. Mech.* **25**: 428–432, Dec. 1958.

The Thomson coefficient, the Peltier coefficient and the electromotive force of a thermocouple, are each expressed in terms of a pure temperature function h which is the difference between the isothermal energy flux in a conductor per unit electrical current and the electrochemical potential of the unit electrical change. The Kelvin relations for the thermocouple follow directly.

391. HENISCH, H. K. **Thermoelectric and conductive properties of blue titanium dioxide.** *Elec. Comm.* **25**: 163–177, June, 1948.

A simple theory of thermoelectric effects in semiconductors is developed. It is shown how measurements of thermopower at various temperatures can be interpreted in terms of the concentration of free charge carriers (electrons or positive holes) and their activation energy. From a comparison of thermoelectric and resistive properties for a series of specimens, conclusions can be drawn as to the relative magnitude of intergranular resistances and the bulk resistivity of individual grains. The thermoelectric properties of TiO_2 (containing a stoichiometric excess of metal) were found to be in substantial agreement with theoretical prediction between 97°K and 617°K. The activation energies thus evaluated were, however, < those obtained from the measurement of resistivity at different temperatures. This and other problems in connection with the interpretation of activation energies are discussed in the light of Lichtenecker's theory of solid mixtures.

392. HENISCH, H. K. **Thermoelectric measurements on semiconductors.** *Phys. Soc. Proc.* **64B**: 1014, Nov. 1951.

The author clarifies some misunderstandings.

393. HERRING, G., GEBALLE, T. H. and KUNZLER, J. E. **Analysis of phonon-drag thermomagnetic effects in *n*-type germanium.** *Bell Sys. Tech. J.* **38**: 657–747, May 1959.

Describes a study which has been made of the Nernst effect and the variation of thermoelectric power with magnetic field for single-crystal samples of n-type germanium of various orientations and impurity concentrations, at fields up to 18,000 gauss and temperatures from 275-60°K and below. Part 2 of a study of which Part I is Item 219, May 1959 issue.

394. HERRING, C. **Role of low energy phonons in thermal conduction.** *Phys. Rev.* **95**: 954–965, Aug. 15, 1954.

Phonon-phonon collisions in which one of the phonons is of low-frequency have become important for understanding of the thermoelectric powers of semiconductors at low temperature. Such collisions are also interesting from the standpoint of thermal conductivity. It is shown here that elastic anistropy has a drastic effect on the collision probabilities of modes of very low frequency.

395. HERRING, C. **The role of low-frequency phonons in thermoelectricity and thermal conduction.** *In* International Colloquium Semiconductors & Phosphors, Proceedings, 1956, p. 184–235, New York Interscience Publishers 1958.

Covers a variety of transport phenomena observable in semiconductors, namely, those which are associated with departure of the low-frequency part of the phonon system from its normal isotropic equilibrium distribution.

396. HERRING, C. **Theory of the thermoelectric power of semiconductors.** *Phys. Rev.* **96**: 1163–1187, Dec. 1, 1954.

Contributions of phonon effect below room temperature; phonons streaming from hot to cold junctions in thermal conduction are assumed to exert drag on charge carriers and to account for marked rise in thermoelectric power with decreasing temperatures.

397. HERRING, C. **Transport properties of a many-valley semiconductor.** *Bell Sys. Tech. J.* **34**: 237–290, Mar. 1955.

In the semiconductor conduction-band model discussed, the energy of an electron, considered as a function of its wave-number vector, has a number of minima, or "valleys". For the valence band the conditions are inverted. For models of this type the theory is developed for (a) mobility and its temperature dependence, (b) thermoelectric power, (c) piezoresistance, (d) Hall effect, (e) hf dielectric constant, and (f) magneto-resistance.

398. HIROSE, ATSUO. **Mathematical theory of multi-dimensional thermoelectricity with some experimental proofs.** *Inst. Elec. Engrs. (Japan) J.* **74**: 1056–1062, Sept. 1954.

The author solves current distributions in long bimetal springs and wide plates, giving their temperature distributions. He also reports some experimental researches.

Lengthy abstract appears in *Japan Sci. Rev. Mech.* and *Elec. Eng.* **1**: 407, June 1955.

399. HOUSTON, W. V. **Electron theory of thermoelectric effects.** *J. Appl. Phys.* **12**: 519–529, Jly. 1941.

The thermoelectric effects considered are the thermoelectromotive force, the Peltier effect, and the Thomson effect.

400. HOWARTH, D. J. and SONDHEIMER, E. H. **The theory of electronic conduction in polar semiconductors.** *Roy. Soc. Proc. London.* **219A**: 53–74, Aug. 11, 1953.

The present problem has been considered before by several authors, but many of the results which have been given are either incorrect or only correct within certain limits. By solving the Boltzmann equation for the velocity distribution function of the conduction electrons in a crystal in which the scattering is due to the polarisation waves of the lattice exact expressions are obtained for the electrical conductivity and the thermoelectric power in the form of ratios of infinite determinants. Simple approximate solutions are derived and are used in the discussion of the dependence of conduction phenomena upon the temperature and upon the degree of degeneracy of the electron gas.

401. IOFFE, A. F., AIRAPETYANTS, S. V., IOFFE, A. V., KOLEMOETS, N. V. and STIL'BANS, L. S. **On improving the efficiency of semiconductor thermoelements.** *Akad. Nauk. SSR. Dok.* **106**: 981, Feb. 21, 1956.

In Russian.

Translation appears in *Infosearch Tech. Lit. Info. Serv. Russian Lit.* Survey SEM-1-56, p. 3.

Consideration of semiconductors in thermoelectric generators and refrigerators leads to three requirements: (1) discovery of materials with a high ratio of electrical carrier mobility to lattice thermal conductivity; (2) carrier concentrations which will result in the optimum thermal emf of ± 200 μV/degree; (3) further increasing the above ratio in these materials. This might be done by making a binary material using a second element as an impurity which crystallises in the same system as the first in such a way that the electrical mobility is little affected but the thermal conductivity is reduced.

402. IOFFE, A. F. **Certain correlations pertaining to the heat conductivity of semiconductors.** *Akad. Nauk. SSSR. Dok.* **97**: 821–822, 1954.

In Russian.

The phonon part of thermal conductivity of semiconductors must decrease with increasing atomic weight. The quantitative results obtained by the authors confirm this prediction.

403. IOFFE, A. F. **Evaluation of the heat conductivity of semiconductors.** *Akad. Nauk. SSSR. Dok.* **87**: 369–372, Nov. 21, 1952.

Formulas are given for determining heat conductivity from the modulus of elasticity, density, and atomic or molecular weight of the material.

404. IOFFE, A. F. **Further development of the theory of semiconductors.** *Soviet Phys. Tech. Phys.* **2**: 1049–1054, June 1957.

Trans. of Russian article in *Zhurn. Tekh. Fiz.*

A survey and analysis of the many successful attempts at theoretical representations of individual features of certain types of semiconductors which still remain to be unified, and amplified before a general theory can emerge. It is already possible to separate characteristics pertaining only to certain ranges and types from those common to all types, i.e., to semiconductors as such.

405. IOFFE, A. F. **Heat transfer in semiconductors.** *Can. J. Phys.* **34**: 1342–1355, 1956.

Measurements of thermal and electrical conductivity in a number of semiconductors are reported and discussed.

406. IOFFE, A. F. **Properties of various semiconductors.** *Phys. & Chem. Solids* **8**: 6–14, figs., 1959.

(Proceedings of 1958 International Conference on Semiconductors).

A general article indicating that problems of thermoelectric cooling, heating and energy production have become a promising field of research,

407. JOHNSON, V. A. and LARK-HOROVITZ, K. **Theory of thermoelectric power in germanium.** *Phys. Rev.* **69**: 259, 1946.

Gives an equation for intrinsic thermoelectric power.

408. JOHNSON, V. A. and LARK-HOROVITZ, K. **Theory of thermoelectric power in semiconductors with applications to germanium.** *Phys. Rev.* **92**: 226–232, Oct. 14, 1953.

The thermoelectric power Q of a semiconductor is found by calculating the Thomson coefficient $\sigma T = T\, dQ/dT$.

409. JOHNSON, V. A. **Theory of the Seebeck effect in semiconductors.** *In* Gibson, A. F. *et. al*, Progress in Semiconductors, v. I, p. 63–97, London, Heywood, 1956.

Review of theory of thermoelectric power.

410. JOHNSON, V. A. **Thermoelectric power in a semiconductor showing high-temperature degeneracy.** *Semiconductor Asb.* **3**: 1159, 1955.

Abstract only of paper given at meeting of the American Physical Society, Chicago, Ill., Nov. 25-26, 1955.

"The narrowness of the forbidden energy band in intermetallic compounds makes it probable that the electron gas at room temperature and above will be sufficiently degenerate to require the use of Fermi–Dirac statistics in expressions for the electrical properties. The thermoelectric power of a semiconductor obeying Fermi-Dirac statistics, considering both holes and electrons, is given for the case of lattice scattering by acoustical modes. Fan and Spitzer have found optical evidence for the combination of acoustical and optical modes of scattering in indium antimonide. Hence the thermoelectric power for optical mode.

411. JONES, H. **The thermoelectric power of monovalent metals.** *Phys. Soc. Proc.* **68A**: 1191–1193, 1955.

It is the purpose of this note to point out that the thermoelectric power is sensitive to the form of the Fermi surface, and that it is not necessary to have the conditions usually associated with "hole conduction" to obtain a positive value.

412. JUSTI, E., KOHLER, M. and LAUTZ, G. **On the dependence of the thermoelectric power of thin metal films on their thickness.** *Naturwiss.* **38**: 475–476, 1951.

In German. Not examined.

A theoretical and experimental examination has been made of the effects of film thickness on the thermoelectric power of films of Bi and Pb as measured against Cu. It is concluded that the effects cannot be explained theoretically on a thermodynamic basis, but can be accounted for in terms of electron theory.

413. JUSTI, E., KOHLER, M. and LAUTZ, G. **Theory of the absolute thermoelectric power of thin metal films and wires.** *Z. Naturforsch.* **6a**: 544–550, Oct. 1951.

In German.

Translation available in Library, British Scientific Research Association, no. 139.

Formulae are developed by assuming that the electron reflection at the boundaries is (a) completely diffuse, or (b) partially elastic. It is found that a variation of the absolute thermoelectric power with thickness indicates a variation of electronic mean free path with energy, and may thus give valuable information. Experimental measurements with lead and bismuth agree well with the theory; values of the mean free paths are calculated. It is shown that the Weidemann-Franz law should still hold.

414. JUSTI, E., KOHLER, M., and LAUTZ, G. **The thermoelectric power of metal films.** *Z. Naturforsch.* **6a**: 456–459, Aug. 1951.

In German.

The thermoelectric power of films of Bi relative to Cu was found to diminish with diminishing film thickness. At a thickness of 100 A it was only about 14% of the normal value. The theory is discussed.

415. KAMMERER, KAMILLO. **The description of thermoelectric phenomena by a temperature-entropy diagram.** *Ann. Physik.* **85**: 948–958, 1928.

In German.

The treatment of thermoelectric effects by the graphical method of Gibbs leads to a generalisation of the thermodynamic laws covering thermoelectric effects.

416. KLEMENS, P. G. **The contribution of phonons to the Thomson coefficient.** *Australian J. Phys.* **7**: 520–522, Sept. 1954.

Note. The contribution μ_p is estimated analytically. For semiconductors μ_p may be appreciable and in general is proportional to the lattice thermal conductivity.

417. KLINGER, M. I. and ZOZULYA, YU. I. **On the theory of semiconductors with an excited impurity-band.** *Zhurn. Tekh. Fiz.* **27**: 2285–2290, Oct. 1957.

In Russian.

The Hall constant, conductivity, and thermo-emf are calculated taking into account excitation and the anistropies of dielectric constant and effective mass. The results are similar to those obtained assuming a fundamental impurity band, and help to explain the existence of impurity bands at low impurity concentrations.

418. KLINGER, M. I. **Theory of transport phenomena in semiconductors.** *Zhurn. Tekh. Fiz.* **27**: 2780–2783, Dec. 1957.

In Russian.

A letter. By introducing the temperature and chemical gradients in the equation of the flow of d matrix first employed by Kubo and Tomita (*Phys. Soc. Japan J.* **9**: 888, 1954) for obtaining a general expression for the electrical conductivity tensor, general expressions for the tensors of thermoelectricity Peltier heat and thermal conductivity, are derived.

419. KOCHER, G. **Measurements of the 3rd-order thermoelectric single-material effect (1st Benedicks effect).** *Ann. Physik.* **16**: 210–226, Sept. 1955.

In German.

The coefficient c_3 in the formula $\mu = c_3 \triangle t$, where μ is the emf and $\triangle t$ is the temperature difference, was determined experimentally using small rectangular loops of Pt, Au and Ag, heated and cooled at two diametrically opposite points. For a loop of dimensions 38−58 mm made of materials with cross-section 4 mm², the value of c^3 was about $-2{\cdot}7 \times 10^{-14}$ V/deg. for Pt, $-4{\cdot}6 \times 10^{-15}$ for Au, and $-2{\cdot}6 \times 10^{-15}$ for Ag.

420. KOHLER, MAX. **Reduktion der thermokraefte auf ideale reinheit der metalle. (Calculation of the thermoelectric force for ideal purity of metals).** *Z. Physik.* **126**: 481–494, figs., 1949.

In German.

It has previously been shown that for metals of varying purity, following the laws of Mathiessen and of Grüneisen and Goens, $\varepsilon = (1\text{-}p)\,\varepsilon_0 + p\varepsilon_i$, where ε is the thermoelectric power as measured, ε_i is the thermoelectric power for the pure metal, ε_0 is a thermoelectric contribution arising from lattice defects and impurities, and p is a constant depending on the residual resistance of the metal and the temperature. From experiments on metals of varying impurity content, ε_0, ε_i and p may be determined from measured values of ε at different temperature. The calculated values of ε_i and even their signs are not in good consistent agreement, and a derived qualitative relation is found to fit the experimental results better. For several metals (Au, Ag, Cu) $\varepsilon/\varepsilon\,\Theta$ is found to yield a universal value as a function of reduced temperature T/Θ for values of T/Θ greater than 0·5, Θ being the characteristic temperature. Below 0·5, there are significant differences between different metals.

421. KONTOROVA, T. A. **Limits of practical application of Pisarenko's formula.** *Zhurn. Tekh. Fiz.* **24**: 1291–1297, Jly. 1954.

In Russian.

Pisarenko's formula expresses thermoelectric power in terms of charge-carrier concentration and effective mass and of absolute temperature. A constant factor is included to take account of scattering of the charge carriers in the crystal; its value depending on the type of scattering and crystal lattice. Calculations show that the errors are small (<5%) up to carrier concentrations of about 2×10^{19} in atomic-lattice and $7{\cdot}2 \times 10^{19}$ in ionic-lattice crystals at 300 K. The errors are discussed, and compared with those of other formulae. Results are tabulated.

422. KONTOROVA, T. A. **Temperature dependence of thermoelectric power of impurity semiconductors.** *Zhurn. Tekh. Fiz.* **24**: 1687–1696, Sept. 1954.

In Russian.

Theoretical considerations show that the large values of the thermoelectric power observed by Frederikse and others at very low temperatures can be accounted for by accepted theory, assuming the electron gas to be highly degenerate in that region. The maximum occurs at the transition from the degenerate state to the "classical" state.

423. KORZH, P. D. **The thermoelectromotive force of some elements at the characteristic temperature.** *Sbornik Nauch. Trudov Magnitorgorsk. Gorno-Met. Inst. No.* **7**: 373–375, 1954. *Referat. Zhurn. Met. No.* 5815, 1956.

In Russian. Not examined.

"From the electronic theory of metals, an expression was derived for specific thermoelectromotive force (I). I was calculated at room temperature and at characteristics temperature θ. The values of I for Pb were compared with the values obtained by empirical relations. Coincidence of theoretical and experimental data for I at temperature θ for the metals of the same group of the periodic system of elements was observed." *Chem. Abs.* **51**: 14344, 1957.

424. LAURILA, E. **On the thermoelectric properties of the impurity semiconductors.** *Acad. Sci. Fennicae, Ann.* **178A**: 11 p., 1955.

In Russian.

Formulas for the Seebeck, Peltier, and Thomson coefficients of impurity semiconductors are derived on the basis of statistical theory of conductivity as developed by Shockley. For a Ge p-n junction at

room temperature the thermoelectric power is found to be about 2 mv/ degrees K.

425. LAUTZ, G. **Zur theorie der differentiellen thermokraft von halbleitern. (Contribution to the theory of the thermoelectric power of semiconductors).** *Z. Naturforsch.* **8A**: 361–371, June 1953.

In German. Translation No. 58–1250 available at Special Libraries Association Translation Center, Crerar Library, Chicago, Ill.

Two formulas are derived for determining the Fermi level, the one applicable at the low temperatures associated with impurity semiconduction and the other applicable at the medium and high temperatures associated with the transition from impurity to intrinsic conditions and with purely intrinsic semiconduction. Expressions for the thermoelectric power are derived which are valid over a wide temperature range. These can be used to determine activation energy, width of energy gap and apparent mass of charge carriers. The limits of validity of the approximate formulas are demonstrated by comparison with exact solutions for two examples. Some experimental results on the temperature dependence of the thermoelectric power are discussed, showing qualitative agreement with the theoretical results.

426. LEECH, J. W. **Irreversible thermodynamics and kinetic theory in the derivation of thermoelectric relations.** *Can. J. Phys.* **37**: 1044–1054, Sept. 1959.

The variety of experimental behaviour found in thermoelectricity at low temperatures provides an incentive for extending the theoretical treatment. In the past, irreversible thermodynamics has been used to provide a satisfactory derivation of the Thomson relations. It appears that what one might call a general "primary equation" of thermoelectricity can be derived from irreversible thermodynamics, and that this should be of direct use in kinetic discussions. The form of the equation suggests that an even more direct approach to the thermoelectric problem should be possible.

427. LOHR, E. **Thermoelectricity, thermo-magnetic and galvanomagnetic transverse effects, treated from the standpoint of the differential equation for the entropy.** *S. B. Ost. Akad. Wiss. Abt. IIa.* **156**: 355–381, 1948.

In German.

The standard thermodynamic treatment of the subject is summarized and its limitations shown. The differential equation for the entropy is derived from Maxwell's second electromagnetic relation, and from the solution and interpretation of this equation all the thermoelectric properties of metals can be deduced, one term of the equation governing the heat conduction and the law of Wiedemann and Franz. The other effects are similarly treated.

428. MACDONALD, D. K. C. and PEARSON, W. B. **Anomalous electron-scattering in metals.** *Phil. Mag.* **45**: 491–496, graphs, May 1954.

Consequences of semi-theoretical equation qualitatively accounting for thermoelectric power of metals and alloys at low temperatures.

429. MACDONALD, D. K. C. **Thermoelectric power in semiconductors.** *Physica* **20**: 996–998, 1954.

Presented at Amsterdam Conference on Semiconductors.

The concept of phonon-electron scattering suggest that electrons are swept along by the lattice waves and may give an additional component of thermoelectric power. The phenomenon is analyzed from direct momentum considerations. The results indicate the need for thermoelectric power measurements in the helium range so as to distinguish between the various processes.

430. MADELUNG, OTFRIED. **Zur theorie der thermoelektrischen effekte in halbleitern. (The theory of thermoelectric effects in semiconductors).** *Z. Naturforsch.* **13a**: 22–25, Jan. 1958.

In German. Translation No. T–381 available from Army Engr. R & D Laboratory.

Mathematical analysis of equations to define the density of energy flow; use of Boltzmann's principle of immobility.

431. MAZUR, P. **Thermopotentials in thermocells.** *J. Chem. Phys.* **58**: 700–702, 1954.

Thermodynamics of irreversible processes is applied to thermocells. Total thermopotential is divided for convenience into a homogeneous and a heterogeneous component. Some general relations between thermopotentials of thermocells and the temperature coefficients for isothermal cells are given.

432. MEISSNER, W. **Remarks on the 1st Benedicks effect.** *Ann. Physik* **16**: 227–228, Sept. 1955.

In German.

Comments on paper by Kocher. The coefficient c_3 may be a function of $\triangle x$, the distance between the two points with temperature difference $\triangle t$; this is of importance when $\triangle x$ is smaller than the mean free path of the conduction electrons.

433. MILLIKAN, R. A. and EYRING, C. F. **Laws governing the pulling of electrons out of metals by intense electrical fields.** *Phys. Rev.* **27**: 51–67, Jan. 1926.

In the experiments herein related new proof was found that the energy of conduction electrons is independent of temperature.

434. MILLIKAN, R. A. and LAURITSEN, C. C. **Relations of field-currents to thermionic currents.** *Natl. Acad. Sci. Proc.* **14**: 45–49, Jan. 15, 1928.

New results presented in this paper may be stated thus: the application of an external field is equivalent to increasing the temperature of the electrons within the metal. A general equation is offered which seems to embrace all the facts of thermionic-currents and field-currents combined.

435. MILNES, A. G. and ALFONSO, N. **Thermoelectric concepts for engineers.** 19 p., figs., New York, American Institute of Electrical Engineers, 1959. (AIEE Paper CP 60–172).

Thermoelectric concepts are presented in terms of simultaneous equations involving current and heat flows. With the aid of the Onsager theorem of statistical mechanics it is shown that the thermoelectric effects are reversible and do not contribute to entropy change in the closed system. The well known thermodynamic relationships between the thermoelectric coefficients follow readily.

To provide some physical understanding of the processes involved, the Seebeck, Peltier and Thomson effects are explained in terms of the energy band structure of a non-degenerate semiconductor.

Although these explanations do not entirely fit the physical conditions of thermoelectric materials used in practice, it is considered that they go some way to meet the needs for engineering type instruction in this subject.

436. MOORE, E. J. **On the galvanomagnetic, thermomagnetic, and thermoelectric effects in isotropic metals and semiconductors.** *Austral. J. Phys.* **11**: 235–254, June 1958.

The calculation of the galvanomagnetic, thermomagnetic and thermoelectric effects in those isotropic metals and semiconductors which can be represented by the two-band model is simplified and extended to cases not previously treated. General expressions are obtained for effects involving time-independent electric fields, magnetic fields, and thermal gradients. Analytic formulae are given for the istothermal galvanomagnetic effects when a high frequency electric field is applied together with a time-independent magnetic field.

Throughout, emphasis is placed on coefficients which are experimentally or theoretically important. The paper concludes with an appendix on the estimation of parameters occurring in the two-band model of metals and semiconductors.

437. MOOSER, E., PEARSON, W. B. and WOODS, S. B. **Thermal and electrical properties of semiconductors.** *In* Conference de Physique des Basses Temperatures, Paris, Sept. 2–8, 1955. Proceedings, p. 420–424, figs, 1955.

The recently reported rapid rise of thermoelectric power of semiconductors with decreasing temperature which is attributed to the interaction between phonons and charge-carriers makes them valuable subjects for the experimental study of such interactions.

438. MORI, H. **A quantum-statistical theory of transport processes.** *Phys. Soc. Japan J.* **11**: 1029–1044, Oct. 1956.

A quantum-statistical method of finding molecular expressions for kinetic coefficients is formulated so as to be applicable to the case where the external disturbance which made a system deviate from equilibrium cannot be taken as a definite additive term in the Hamiltonian of the system, such as the heat conduction and the viscous flow. This method provides an extension of the fluctuation-dissipation theorem to such quantum-mechanical systems. A quantum-statistical expression for the entropy of a non-equilibrium system is defined so as to be consistent with Gibb's relation, and is shown to give a quantum-statistical basis for the thermodynamics of irreversible processes. Two ways of applying this method to each special system are shown; one is concerned with deriving the phenomenological equations of motion, and the other with calculating the entropy production of the system. Thus, quantum-statistical expressions are obtained for the relaxation time of an energy transfer between two sub-systems and that of momentum relaxation phenomena, and for the coefficients of thermoelectricity.

439. MOTT, N. F. and JONES, H. **The theory of the properties of metals and alloys.** 326 p., figs., Oxford, Clarendon Press, 1936.

Thermal conductivity and thermoelectricity, p. 305–314.

440. MITSOVICH, V. M. **K teorii kineticheskikh iavlenii v poluprovodnikakh s uzhoi primesnoi zonoi. (On the theory of kinetic phenomena in semiconductors with a narrow impurity zone).** *Zhurn. Tekh. Fiz.* **28**: 1201–1206, June 1958.

In Russian.

Effects of the correlation between the electrons on the kinetics of the processes in a narrow impurity zone in calculating the compensating impurity. The results were used in drawing formulas of electric conductivity of the Hall constant effect and to the thermo-emf in semiconductors in the presence of a narrow impurity zone.

441. NORDHEIM, L. and GORTER, C. J. **Bemerkungen ueber thermokraft und widerstand. (Observations of thermoelectric force and resistance).** *Physica* **II**: 383–390, 1935.

In German.

Any perturbation introduced into a metal will give rise to an increased resistance and to a change in the thermoelectric power. Under certain circumstances a parallelism between these two changes may be expected. After a short review of the theoretical formulas, the following cases are considered from a theoretical as from an experimental point of view: solid solutions, ferromagnetic substances, cold-worked and liquid metals.

442. Ohta, Tokio. **Effect of charged dislocation on the thermoelectric power of semiconductors.** *Phys. Soc. Japan. J.* **15**: 197, Jan. 1960.

Effects of the cylinder of the space charge on the T.E.P. of semiconductors.

443. PARROTT, J. E. **The effects of heat flow on the thermoelectric power in semiconductors.** *Phys. Soc. Proc.* **67B**: 587–588, Jly. 1954.

The effects due to conduction of heat by the lattice vibrations are considered from a more physical approach than the formal treatments due to Gurevich and to Frederikse. Reasonable agreement with experiment is obtained.

444. PARROTT, J. E. **Some contributions to the theory of electrical conductivity. Thermal conductivity and thermoelectric power in semiconductors.** *Phys. Soc. Proc.* **70B**: 590–607, June 1, 1957.

The theory of transport phenomena in semiconductors is extended to include the effects of "phonon drag" on electrons and "electron drag" on phonons.

445. PERRIER, A. and BLUMER, O. **Limite superieure de l'effect Nernst-v. Ettingshausen et du pouvoir thermoelectrique intrinsique du plomb. (Upper limit of the nernst-ettingshausen effect and the thermoelectric power of lead).** *Helv. Phys. Acta* **26**: 567–568, Nov. 16, 1953.

In French.

Thermoelectric effects of lead.

446. PRICE, P. J. **On the statistical mechanics of impurity conduction in semiconductors.** *IBM J. Res. & Dev.* **2**: 123–129, Apr. 1958.

The case of low donor density with partial acceptor compensation is analyzed on the basis of the Mott model. An expression for the thermoelectric power is obtained. The special case of mixed donors in disparate proportions is also considered.

447. PRICE, P. J. **Theory of transport effects in semiconductors: the Nernst coefficient, and its relation to thermoelectric power.** *Phys. Rev.* **102**: 1245–1251, June 1, 1956.

Theory presented previously is extended to give an expression consistent with that derived by Putley for the complete Nernst coefficient. The information obtainable from experimental values of this coefficient and of the thermoelectric power is discussed in the light of the theory. An estimate is made of the anomaly in the Nernst coefficient due to the phonon drag effect.

448. PRICE, P. J. **Theory of transport effects in semiconductors: thermoelectricity.** *Phys. Rev.* **104**: 1223–1239, Dec. 1, 1956.

The phenomenological theory of thermoelectric effects in a cubic or isotropic electronic conductor is developed, and the general formulas obtained are applicable to a two-band semiconductor. The valuation of data for mixed semiconductors is discussed and experimental results for Ge are analyzed. The effects of a strong magnetic field and of strain are considered.

449. RITTNER, E. S. **On the theory of the Peltier heat pump.** *J. Appl. Phys.* **30**: 702–707, May, 1959.

Figure of merit for a single stage heat pump is optimised in the region of partial Fermi degeneracy. A more rigorous treatment is presented of the properties of a cascade operating at maximum coefficient of performance. The heat leak in the absence of current flow is called to attention as a serious problem in devices with excess capacity.

450. RODOT, MICHEL. **Transport effects in indium antimonide.** *Phys. & Chem. Solids* **8**: 358–361, 1959.

Report of International Conference on Semiconductors.

A theory of thermoelectric, Nernst, and magnetothermoelectric phenomena is applied to special cases, by assuming various dispersion mechanisms to be operative. Comparison with experimental data seems to show that in InSb, polar dispersion by optical phonons predominates. The ambipolar effect is briefly discussed and shown to be insensitive to the scattering mechanism.

451. ROSE, F. W. G., BILLIG, E. and PARROTT, J. E. **A simple derivation of the thermoelectric voltage in a nondegenerate semiconductor.** *J. Electron. Contr.* **3**: 481–486, Nov. 1957.

Only concepts such as Fermi levels, field current, diffusion current, etc., are used in the derivation.

452. SAMOILOVICH, A. G. and KORENBLIT, L. L. **Contemporary status of the theory of thermoelectric and thermomagnetic phenomena in semiconductors. Pt. II.** *Usp. Fiz. Nauk.* **49**: 337–383, Mar. 1953.

In Russian.

A review based on the generally prevailing "single electron" theory of conduction.

For Part I entry, see Item 487, May 1959 issue.

453. SAMOILOVICH, A. G. **O prirode termoelektricheskikh iavlenii. (Nature of thermoelectric phenomena).** *Zhurn. Tekh. Fiz.* **25**: 823–826, May 1955.

Mathematical analysis and discussion of theories. Consideration of the irreversibility of thermal conductivity, difference of entropies of electrons, and chemical potentials of electrons in metals.

454. SHABANSKII, V. P. **Transport processes in conductors taking into account non-linear effects.** *Zhurn. Eksp. i Teor. Fiz.* **31**: 657–671, Oct. 1956.

In Russian.

Relaxation processes in the electron lattice system analysed and equations obtained for the heating of electron gas in strong electric fields. The kinetic equations are solved for particular cases and galvanomagnetic and TE phenomena discussed. Theory is applicable to semiconductors in the region of conduction electron degeneracy.

455. SONDHEIMER, E. H. **Electron-phonon equilibrium and the transport phenomena in metals at low temperatures.** *Can. J. Phys.* **34**: 1246–1255, Dec. 1956.

Points out the fact that the term Qg which arises from the non-equilibrium of the lattice appears to play an important part in determining the thermoelectric behaviour of metals.

456. SONDHEIMER, E. H. **Kelvin relations in thermoelectricity.** *Roy. Soc. London. Proc.* **234A**: 391–398, Feb. 21, 1956.

A general proof is given of the Kelvin relations among the thermoelectric effects in conducting crystals, the departure from equilibrium of both

the electron and the lattice distribution functions being taken into account. It is emphasised that the theory of the transport phenomena in conductors must be formulated so as to treat the mutual interaction between electrons and lattice vibrations in a fully symmetrical way.

457. SONDHEIMER, E. H. **The theory of the galvanomagnetic and thermomagnetic effect in metals.** *Roy. Soc. London. Proc.* **193A**: 484–512, Jly. 21, 1948.

The methods of a previous paper are used to discuss the effect of a magnetic field on the thermoelectric power of a metal containing two overlapping energy bands of normal form. Exact solutions of the transport equation are obtained for the three limiting cases of high temperatures, low temperatures and very strong magnetic fields, and it is shown that the formulae can be generalised to give approximate expressions for all temperatures and all fields.

458. SONDHEIMER, E. H. **The theory of the thermoelectric power of metals.** *Camb. Phil. Soc. Proc.* **43**: 571–576, 1947.

Shows that it is possible to set up an expression for the thermoelectric power of the same type as the interpolation formulas for the electrical and thermal conductivities.

459. SONDHEIMER, E. H. **The theory of the transport phenomena in metals.** *Roy. Soc. London. Proc.* **203A**: 75–98, Sept. 7, 1950.

Exact expressions, valid for all temperatures, are obtained in the form of infinite determinants for the electrical conductivity, the thermal conductivity and the thermoelectric power of a degenerate gas of quasi-free electrons interacting with the ionic lattice of a metal. It is shown that the value of the electrical and thermal conductivities, in general, exceeds the values given by the approximate interpolation formulae given by Bloch, Wilson and others, and, in particular, that the Grüneisen-Bloch formula for the ideal electrical resistance is appreciably in error in the region close to the Debye temperature. It is further shown that the residual and ideal resistances of an impure metal are not strictly additive in the region where the two are of the same order of magnitude. The behaviour of the thermal conductivity is shown to agree qualitatively with the discussion based on Wilson's formula given by Makinson; the numerical values of the thermal conductivity however, are increased appreciably particularly for an ideal metal at low temperatures. The thermoelectric power is also discussed, but no simple results can be given for the intermediate temperature range.

460. STAVITSKAIA, T. S. and STIL'BANS, L. S. **O vliianii vyrozhdeniia na effektivnost' poluprovodnikovykh termoelementov. (Effect of degeneration on the efficiency of semiconductor thermoelectric cells).** *Zhurn. Tekh. Fiz.* **28**: 484–488, Mar. 1958.

In Russian.

Translation in Infosearch Tech. Lit. Info Serv. Russian Lit. Survey SEM-5-58, p. 10.1—10.5. See also *Sov. Phys. Tech. Phys.* **3**: 456–459, Mar. 1958.

A comparison of theoretical and experimental data.

461. STRATTON, R. **On the elementary theory of thermoelectric phenomena.** *Brit. J. Appl. Phys.* **8**: 315–321, Aug. 1957.

Theory of thermoelectric phenomena is deduced from general theory of conduction in metal or semiconductor; calculation discussed in detail to bring out significance of various thermoelectric parameters; all relations between the thermoelectric parameters are deduced from physical properties rather than by simply carrying out mathematical transformations; sources of heat and emf are indicated.

462. TAKENO, SHOZO. **Thermoelectric effect in univalent metals.** *Busseiron Kenkyu no.* **96**: 37–48, 1956.

Not examined.

Mathematical and theoretical. (*Chem. Abs.* **51**: 5536, 1957).

463. TAUC, JAN. **Note on the theory of the anomalous thermoelectric phenomenon in semiconductors.** *Czechoslov. J. Phys.* **7**: 376–377, 1957.

In Russian.

An earlier paper described the anomalous variation of the thermo emf, $\triangle U$, with temperature that had been observed in n-type Ge in the case when a tungsten point constituted the cold electrode, and attributed this effect to the thermoemission of holes. In the present note an expression is derived which describes the temperature dependence of $\triangle U$ and which is in qualitative agreement with experimental results previously obtained.

464. TAUC. JAN. **On the theory of thermoelectricity.** *Phys. Soc. Japan. J.* **14**: 1174–1175, Sept. 1959.

The meaning of the inner electrical field inside a two-band semiconductor the gap of which depends on temperature is discussed in connection with the theory of the thermoelectromotive force in such semiconductors.

465. TAUC, JAN and TROUSIL, Z. **The effect of thermal emission of holes on the thermal emf of n-type semiconductors.** *Czechoslov. J. Phys.* **3**: 120–125, 1953.

In Russian.

On measuring the thermal emf of n-type semiconductors, it was observed that the character of the dependence of the temperature was different when using a cold point and a heated flat electrode from that when using two flat electrodes. This effect can be explained theoretically by the following conception. Under the point electrode a large temperature gradient is created which, due to the diffusion of holes from warmer parts, causes a greater concentration of the current carriers in the

cooler parts than corresponds to the equilibrium value. The potential barrier under the point prevents the electrons from entering the contact but does not prevent the penetration of the holes. The excess of holes causes an electric voltage analogous to that in a barrier layer cell.

466. TAUC, J. **Theory of the thermal emf of semiconductors.** *Czechoslov. J. Phys.* **3**: 282–303, 1953.

After a discussion of the present theory of the thermal emf of semiconductors, the theory is extended to non-homogeneous semiconductors. Its relationship to thermodynamics is discussed, and it is then applied to the study of the influence of potential barriers. Further cases are discussed in which the velocity or the concentration of electrons does not conform to a state of thermal equilibrium as in the case of diode-type barriers or for injected current carriers. The results are applied to a discussion of the influence of high temperature gradients. The influence of minority current carriers on thermal-emf is systematically treated. Equations are derived and the magnitudes of certain anomalous effects are estimated. Some of these have not yet been experimentally observed.

467. TAUC, J. **Theory of thermoelectric power in semiconductors.** *Phys. Rev.* **95**: 1394–1402, Sept. 15, 1954.

Corrects error in paper by Johnson and Lark-Horowitz by calculating the TE power directly from the electrical current density expression. A general equation for TE power is given which holds for semiconductors with one or two kinds of current carriers in thermal equilibrium governed by classical or Fermi–Dirac statistics.

468. TAUTS, A. **Thermoelectric phenomena in semiconductors with a non-equilibrium concentration of current carriers.** *Izvest. Akad. Nauk. SSSR. Ser. Fiz.* **21**: 1957, p. 1479–1483.

In Russian.

Paper given at 8th Conference on semiconductors at Leningrad, Nov. 15-21, 1955.

Thermal emf measured on a Ge single-crystal surface with a W point is quite different from the emf measured with flat electrodes because in this case a nonuniform distribution of holes tends to change the sign of the charge on the point contact. In this case the nonuniform distribution is due to a temperature gradient. In the region of the temperature drop the concentration of minority carriers is a nonequilibrium value which leads to a further correction for the observed emf. An experimental installation is described to determine the emf dependence on temperature gradient in Ge single crystals. A nonuniform hole concentration can also be produced by illumination. If illumination is combined with a temperature gradient, a new effect ("thermal photoeffect") is obtained. A photovoltaic voltage is produced. The emf difference is given by formula and an experimental value was obtained in preliminary tests.

469. TER HAAR, D. and NEAVES, A. **On the thermal conductivity and thermoelectric power of semiconductors.** *Adv. in Phys.* **5**: 241–269, Apr. 1956.

A comprehensive discussion of scattering mechanisms in semiconductors, neglecting the influence of deviations from spherical energy surfaces and of many-lectron phenomena, and assuming only one type of carrier to be present. Six temperature ranges are hence distinguished; expressions are derived for the thermal conductivity and thermoelectric power in each range. The theoretical results are in qualitative agreement with such experimental results as are available.

470. TEL HAAR, D. and NEAVES, A. **On the thermoelectric power of metals.** *Roy. Soc. London. Proc.* **228A**: 568–574, Mar. 22, 1955.

A theoretical paper based on a method employed by Makinson. An expression is derived for the contribution of the lattice current to the thermoelectric power of metals at temperatures where electron-phonon scattering predominates. In this range the thermoelectric effect will be of opposite sign to that which follows from simple electron theory of metals. The effect discussed cannot explain the known behaviour of alkali metals completely.

471. TER HAAR, D. **On the transport properties of metals and semiconductors.** *Physica*, **22**: 61–68, Jan. 1956.

Simple kinetic theory is used to derive approximate expressions for the thermal conductivity, electrical conductivity, thermoelectric power, Hall constant, and magneto-resistance of metals and semiconductors.

472. THOMSON, WILLIAM. **On the dynamical theory of heat. Part V. thermo-electric currents.** *Roy. Soc. Edinburgh. Trans.* **21**: 123–171, figs., 1857.

The object of the present communication is to extend the theory of electric currents (communicated to the Royal Society, Dec. 15, 1851) to the phenomena of thermoelectricity in crystalline metals.

473. TOLPYGO, K. B. and FEDORCHENKO, A. M. **Interaction between an electron hole and lattice oscillations in a homopolar crystal.** *Zhurn. Eksp. i Teor. Fiz.* **31**: 845–853, Nov. 1956.

In Russian.

Motion of a hole in a homopolar crystal of the diamond type is considered on the basis of the many-electron Schrodinger equation. The presence of a hole was taken into account by replacing a single pair bond by a one-electron bond, with the result of an additional force which tends to deform the crystal. The corresponding term in the Hamiltonian was interpreted as the interaction between the hole and the lattice dislocations. The significance for the problem of autolocalisation of the hole of the forces which thus arise, the scattering of current carriers by lattice vibrations and the

theory of mobility, the thermo-emf and the Nernst effect, are also discussed.

474. TSUJI, MIKIO. **Electron transport in metals.** *Phys. Soc. Japan J.* **12**: 828–829, 1957.

Author extends and corrects Barrie's calculation (*Phys. Rev.* **103**: 1581, 1956) of the change produced in the conductivity and thermoelectric power of metals when the Bohm-Pines E_k/k curve is used instead of the usual parabolic one. Arbitrary temperature and impurity concentrations are considered. Deviations of the band structure from the free-electron model have an important effect on the thermoelectric power.

475. TSUJI, MIKIO. **Localized electron model and thermoelectric power.** *Phys. Soc. Japan J.* **14**: 1640, Nov. 1959.

Note. "From his analysis of the results of the measurements of the electrical conductivities and the thermoelectric powers of α-Fe_2O_3, and NiO, Morin has derived a conclusion that the mobilities of the carriers of the crystals have a strong temperature dependency which should be described in terms of activation energies for the transport of carriers. In the present note, we shall derive a formula of the thermoelectric power of a crystal in which carriers are tightly bound to ions and the jumping of a carrier from one ion to another need an activation energy, and show that Morin's analysis is not satisfactorily consistent."

476. TSUJI, MIKIO. **The thermoelectric, galvanomagnetic and thermomagnetic effects of monovalent metals. I.** *Phys. Soc. Japan. J.* **13**: 133–148, Feb. 1948.

Theory is based on model of general spherical energy band. Effect of the Umklapp processes on time of relaxation at high temperatures is investigated.

477. TSUJI, MIKIO. **The thermoelectric, galvanomagnetic and thermomagnetic effects of monovalent metals. II. The thermoelectric powder (SIC) for anisotropic media.** *Phys. Soc. Japan. J.* **13**: 818–827, Aug. 1958.

In Part II, the thermoelectric power at low temperatures is calculated for an arbitrarily anisotropic energy band. The results show that there is a possibility to give positive thermoelectric powder (sic) for pure metals at low temperatures if the shape of the energy surface is appropriate. The relation with the spherical band model used in Part I is discussed also.

478. TSUJI, MIKIO. **The thermoelectric, galvanomagnetic and thermomagnetic effects of monovalent metals, IV. Effect of the non-equilibrium distribution of the phonons.** *Phys. Soc. Japan. J.* **14**: 618–632, May 1959.

The effects of the non-equilibrium distribution of the phonons on the electrical and thermal conductivities, thermoelectric power, and transverse galvano- and thermomagnetic effects of metals are calculated. It is shown that Onsager's reciprocal relation holds, actually, in the case of the non-equilibrium distribution of the phonons with presence of a magnetic field. For the spherical band model, the effect on the Ettingshausen-Nernst coefficient is not so large as appeared in literatures. For an anisotropic band model, the phonon drag terms appear in the Ettingshausen, Ettingshausen-Nernst and Righi-Leduc coefficients.

479. URE, R. W. **Effect of impurity scattering on the figure of merit of thermoelectric materials.** *J. Appl. Phys.* **30**: 1922–1924, Dec. 1959.

The thermoelectric figure of merit $z=a^2/\rho K$ is calculated for an extrinsic semiconductor with mixed acoustic-mode lattice scattering and ionised-impurity scattering. The result is compared to the value for pure acoustic-mode scattering. As the amount of ionised-impurity scattering is increased, the figure of merit increases by less than 10% and then falls slowly.

480. VAN DER PAUW, L. J. and POLDER, D. **Photo-thermoelectric phenomenon in semiconductors.** *J. Electron.* **2**: 239–240, Nov. 1956.

Reference to effect in which thermoelectric power is influenced by external light; phenomenon has previously been calculated under assumption that energy gap between conduction band and valence band is independent of temperature; by calculating difference of Fermi levels of hot and cold part of semiconductor new expression is derived for photothermoelectric phenomenon.

481. VERSCHAFFELT, J. E. **The thermodynamics of thermoelectricity. II.** *Acad. Roy. Belge. Bull. Classe. Sci.* **35**: 193–206, 1950.

In French.

The ideas of the author's first paper are further developed. The fundamental equations for a crystal with both translational and rotational anisotropy are established, and the Bridgman effect is explained in terms of the tensor character of the entropy. It is considered that the tensor is symmetrical and in the case of simple rotational anisotropy it becomes a scalar.

482. VUL, B. M. **Breakdown of transition layers in semiconductors.** *Zhurn. Tekh. Fiz.* **26**: 2403–2416, Nov. 1956.

In Russian.

The electrical, thermal, and thermoelectric factors in the breakdown of a p-n junction are discussed theoretically.

483. WILSON, A. H. **The theory of metals.** 346 p., figs., Cambridge, University Press, 1933.

The thermoelectric effects, p. 202–208.

484. WILSON, A. H. **Transport phenomena in metals.** *Physica* **24**: S98–S101, Sept. 1958.

Discusses the thermoelectric force at normal temperatures.

485. WRIGHT, R. W. **The effect of the mean free path of electrons of the electrical properties of nonmetals.** *Phys. Soc. Proc.* **64B**: 984–999, Nov. 1, 1951.

The theories of the mean free path of electrons in various types of materials, under various conditions, are discussed. The conductivity, thermoelectric power, Hall coefficient, fractional change of conductivity in a magnetic field, and the Nernst, Ettingshausen, and Righi-Leduc coefficients are all calculated upon the Lorenz-Sommerfeld theory for the various mean-free-path theories. The variations are discussed with particular respect to the changes of reduced chemical potential. Experimental evidence is discussed and is found in general to support the theory given, both in impurity metals and semiconductors, except perhaps in the case of the thermoelectric power.

486. YAMASHITA, JIRO. **Theory of thermoelectromotive force in semiconductors.** *Phys. Soc. Japan. J.* **4**: 310–215, 1949.

An attempt to obtain improved formulae for the temperature dependence of the thermoelectric power of semiconductors. The Boltzmann equation of state is quoted in a general form and solved for the free electron case. The expression for the thermoelectric power differs from the usual one and is in satisfactory agreement with experiments on ZnO and Cu_2O. An expression derived on the assumptions that two types of impurity centres are present is capable of explaining turning points and approximately horizontal portions of the characteristics.

487. YURKOV, B. YA. **On the theory of semiconductor energy converters.** *Zhurn. Tekh. Fiz.* **28**: 1365–1370, Jly. 1958.

Translation in Infosearch Ltd. Russian Lit. Survey SEM-7-59.

On the basis of the theory of electron energy losses proposed by Spencer, a theory is evolved for a semiconductor converter of the energy of monoenergetic electrons into electrical energy. An expression convenient for practical calculations is derived for the generation current (short circuit current) of the converter.

488. ZENER, CLARENCE. **D-band and mixed-valency semiconductors.** *Phys. & Chem. Solids* **8**: 26–28, Jan. 1959.

Proceedings of 1958 International Conference on Semiconductors.

The concept of electrical conduction by the activated jumping of localised charge carriers leads to certain predictions. One of them relates to the thermoelectric power of doped transition-metal oxides.

489. ZIL'BERMAN, G. E. **Thermo- and galvanomagnetic effects in strong fields at low temperatures.** *Zhurn. Eksp. i Teor. Fiz.* **29**: 762–769, Dec. 1955.

In Russian.

Thermoelectric force, Hall effect of a metal in a magnetic field at low temperatures are calculated using a two-zone model of the metal.

490. ZIMAN, J. M. **The thermoelectric power of the alkali metals at low temperatures.** *Phil. Mag.* **4**: 371–379, Mar. 1959.

The effect of phonon drag is calculated, taking account of electron-phonon Umklapp processes, and anisotropy of the Fermi surface. For Na, the observations are perfectly fitted with a spherical surface. For K, Rb and Cs, the surfaces must bulge more than halfway towards the faces of the Brillouin zone, while in Li it probably touches the zone boundary.

MATERIALS

(Properties)

491. ABLOVA, M. S. and REGEL, A. R. **Thermoelectric power of germanium near the melting point.** *Zhurn. Tekh. Fiz.* **27**: 2170–2172, Sept. 1957.

In Russian.

Trans. in *Sov. Phys. Tech. Phys.* **2**: 2012–2013, Sept. 1957.

Careful measurements of the thermoelectric power of germanium were made up to about 850–900°C. and the results extrapolated to the melting point. Values of order −5 to −100 μV/deg.C were obtained and seemed to indicate that the actual value was determined by the degree of constraint in the specimen which was still marked, even at high temperatures. The more compressed the sample, the lower was the thermoelectric power. The results are consistent with the well-known increase in acceptors in Ge brought about by plastic deformation.

492. ABRAHAMS, M. S., BRAUNSTEIN, R. and ROSI, F. D. **Thermal electrical and optical properties of (In, Ga)As Alloys.** *Phys. & Chem. Solids* **10**: 204–210, illus., Jly. 1959.

The (In, Ga)As system exhibits complete solid miscibility. Homogeneous alloys were produced across the entire system by using the method of zone-levelling. Physical measurements hsow that the lattice thermal conductivity decreases markedly with alloying and exhibits a minimum value of about 0·05 Wdeg.$^{-1}$ cm^{-1} at an alloying composition of about 50%. The thermoelectric power varies linearly with the logarithm of the carrier concentration for non-degenerate crystals, and from these data it appears that the "density of states mass" is independent of alloying. The mobility of electrons decreases monotonically with increasing percentages, up to about 70% of GaAs. The band gap varies continuously with composition, and a concave upward dependence is observed on going from InAs to GaAs.

493. ABRIKOSOV, N. K. and BANKINA, U. F. **Termoelektricheskii svoistva soedineniaa $CrSb_2$. (Thermoelectric properties of the compound $CrSb_2$).** *Akad. Nauk. SSSR. Dok.* **108**: 627–628, June, 1956.

In Russian.

The temperature coefficient of thermoelectric force of this semiconducting compound varies between −81μV/°C. at 18 C. and −22μV/°C. at 437 C., the conductivity at these temperatures being 6·4Ω^{-1}. cm^{-1}, and 43·5Ω. cm^{-1}, respectively. Results of measurements between these temperatures are tabulated and the effect of a small variation of the composition of the compound on the conductivity and thermoelectric force at 550°C is shown graphically.

494. ABRIKOSOV, N. KH., DYUL'DINA, K. A. and DANILYAN, T. A. **The SnTe-PbTe System.** *Zhurn. Neorg. Khim.* **3**: 1632–1636, 1958.

In Russian.

The phase diagram and the thermoelectric properties of the SnTe–PbTe system were studied. For the ternary system Pb–Sn–Te, a continuous series of solid solutions is formed along the SnTe–PbTe diagonal. The conductivity, thermal emf and the micro-hardness were determined for alloys of SnTe and PbTe having the same type of conductivity and having different types of conductivity.

495. ABRIKOSOV, N. K., DYUL'DINA, K. A. and DANILYAN, T. A. **Investigation of the SnTe-PbTe system.** *Zhurn. Neorg. Khim.* **3**: 1632–1636, Jly. 1958.

Translation in Infosearch Ltd. Russian Lit. Survey SEM-7-59.

A continuous series of solid solutions forms along the SnTe–PbTe section in the ternary system Pb–Sn–Te. The equilibrium diagram is lenticular in shape.

Electrical conductivity and thermal emf of alloys prepared from SnTe and PbTe specimens with the same type of conductivity vary along smooth curves with the convex side facing the axis of abscissae.

Variations of properties of alloys prepared from SnTe and PbTe specimens with different types of conductivity have a complex nature; maxima of the absolute value of the thermal emf are observed in both portions of the system, the maximum being positive for alloys rich in SnTe and negative for alloys rich in PbTe. Electrical conductivity of the alloys exhibits a minimum. Such variations in the properties of the alloys may be attributed to the interaction of positive and negative current carriers and a reduction of their concentration as a result of this interaction, which leads, as predicted by theory, to an increased absolute value of the thermal emf and a drop in the electrical conductivity.

Article with same title also in *Akad. Nauk. SSSR. Dok.* **123**: 279–281, Nov. 11, 1958.

496. ABRIKOSOV, N. K., VASSERMAN, A. M. and PORETSKAYA, L. V. **Investigation of the tin telluride-germanium telluride system.** *Akad. Nauk. SSSR. Dok.* **123**: 279–281, 1958.

In Russian.

The SnTe–GeTe section of the Ge–Sn–Te equilibrium diagram was studied by thermal analysis, X-ray measurement of the lattice constant, and measurement of the microhardness (H), electrical conductivity (σ), and thermo-emf against Cu (α). The equilibrium state of the alloys was controlled by examining the microstructure. using 1 : 1 HNO_3 as etchant. A continuous series

of solid solution is formed, with a minimum melting point at ~80% GeTe and 700°C; there was a gradual change from the cubic f.c.c. lattice of SnTe into the rhombohedral f.c.c. lattice of GeTe. H passed through a maximum at ~60% GeTe, σ a minimum at ~60 GeTe, and α a maximum at ~20% GeTe.

497. ABRIKOSOV, N. K. **Iron-silicon system in the $FeSi_2$ compound range.** *Akad. Nauk. SSSR. Izvest. Sektora Fiz-Khim. Anal., Inst. Obshchei i Neorg. Khim.* **27**: 157–163, 1956.

In Russian. Not examined.

"Alloy samples were prepared from Armco iron and 99·95% pure Si, by fusing the mixtures in the required proportion in a high-frequency furnace. The samples were microphotographed, and later annealed at 1000° for five days; alloys with a composition close to $FeSi_2$ were also annealed at 900° for 40 days, and quenched in water. The quenched samples were studied metallographically, thermographically, by X-ray analysis, and by the emf determination vs. Cu. The composition of the samples around $FeSi_2$ was changed in amounts of 1% by weight of Si. A FeSi + Se eutectic was found to form with about 54% Si. The shape of the curve leads to an assumption of $FeSi_2$ decomposing at the melting point. The thermoelectromotive force and the phase diagram of alloys with 46–66 weight% of Si are reproduced." *Chem. Abs.* **50**: 15380, 1956.

498. ABRIKOSOV, N. K. and BANKINA, V. F. **Study of the phase diagram of the system Bi-Te.** *Zhurn. Neorg. Khim.* **3**: 659–667, 1958.

In Russian.

The system Bi–Te (up to 54% Te) was studied by the method of thermal analysis, electrical conductivity, thermo-emf and X-ray structural analysis. The thermo-emf was measured in relation to Cu with a difference of temperature of about 20°. The samples were prepared by fusing Bi (reduced from oxide, distilled in vacuo) and Te (melted under a layer of carbon, twice distilled in vacuo) in evacuated quartz ampoules. The duration of the experiment was 2–4 months. In the system Bi-Te, besides the compound Bi_2Te_3 three intermediate phases were found: (1) the phase $Bi_{14}Te_6$, corresponding to the composition of the mineral khedlite (formed by a peritectic reaction at 312°); (2) solid solution based on the compound Bi_2Te, spread out over the range 22·5–26% Te (formed by a peritectic reaction at 420°); (3) a similar region of solutions within the range 34–42·5% Te (formed by a peritectic reaction at 540°). The solubility of Te in the compound Bi_2Te_3 is about 1%; the solubility of Bi on Te was not found.

499. AFANES'EV, N. V. **Effect of sulfur on the effect of selenium.** *Zhurn. Tekh. Fiz.* **19**: 225–230, 1949.

In Russian.

S (>5%) increases the electrical conductivity of Se; at 0–60° the conductivity of Se and S–Se mixtures increases exponentially with rising temperatures. The higher the S content, the smaller the extent by which the work of dissociation and conductivity change with S content. The TE coefficient of the couple CuSe–S at 3 to 110° increases with temperature and decreases with decreasing dissociation work, increasing conductivity, and increasing S content. The hot ends of the Cu–Se and Cu–S couples acquire a negative potential indicating the predominant "hole" conductivity of both pure Se and Se–S mixtures.

500. AGLADZE, R. I. and MOKHOV, V. M. **Alloys of manganese with copper.** *Akad. Nauk. Gruzin. SSR. Soobshcheniya.* **15**: 33–40, 1954.

In Russian. Not examined.

"High-resistance alloys, containing 65–69% Mn, the balance Cu, have good hot-and-cold-workability. The limiting electric resistivity, p, is 1·79–1·92 ohm mm²./m.; the temperature coefficient of the electric resistivity varies from -6×10^{-5} to $+6\times10^{-5}$ between 25 and 35°; the thermal emf of the alloy-Cu couple is not more than 1 microv in 1°; the electric resistivity is stable with time These properties make the alloy useful in rheostats operating at 100–50°. Plasticity of the alloy is adversely affected by more than 0·2–0·3% Si, but not by Al (up to 3·5%) or Fe (up to 1%), as is the accepted view; up to 0·03% S is not harmful." *Chem. Abs.* **50**: 3983, 1956.

501. AIGRAM, PIERRE, RIGAUX, CLAUDETTE and THUILLIER, J. M. **Thermomagnetoelectric effects in indium antimonide.** *Acad. Sci. Paris. Compt. Rend.* **242**: 1145–1148, 1956.

In French.

Electric conductivity (I), Hall effect, (II), thermoelectric effect, (III), and Nernst effect, (IV), were investigated for an In–Sb alloy. Above 400°K, I followed the theoretical law A exp (−e/2kT), where e was 0·24 eV. The constant of II was zero at 313° and reached a minimum at 443°K. III was in accord with the theory for a semiconductor. IV was also in accord with the theory with a maximum at 423°K. The good agreement of these observations with theory of semiconductors permits the simple determination of the ratio of the numbers of electrons to holes and the mobility of each type of carrier.

502. AINSWORTH, L. **Single crystal bismuth telluride.** *Phys. Soc. Proc.* **69B**: 606–612, June 1, 1956.

Production of p-type crystals of Bi_2Te_3 by withdrawing from the melt in a hydrogen atmosphere; thermoelectric power coefficient was 200 to 215 μV/C even with considerable departures from stoichiometric proportions; optical energy gap was 0·15 eV; conductivity was 500/ohm-cm. parallel to cleavage planes; possible applications for thermoelectric devices discussed.

503. AIRAPETYANTS, S. V. and EFIMOVA, B. A. **The thermoelectric properties and the bonding in the system Bi_2Te_3+Sb_2Te_3.** *Zhurn. Tekh. Fiz.* **28**: 1768–1774, Aug. 1958.

In Russian.

Based on the analysis of the structure of Bi_2Te_3, Bi_2Se_3, Sb_2Te_3, the conclusion is drawn that in Bi_2Te_3 and the alloy $Bi_2Te_3 + Sb_2Te_3$ there are 3 types of bonds; (a) ionic, (b) covalent, and (c) weak residual. A study is made of the thermoelectric properties of polycrystalline specimens; ordering is detected in the solid solution for the compositions 1/3 Bi_2Te_3 + 2/3 Sb_2Te_3 and 2/3 Bi_2Te_3 + 1/3 Sb_2Te_3. A method is proposed for determing the width of the forbidden band from the measurements of thermal emf.

For translation see Trans. TA-23, Massachusetts Institute of Technology, Lincoln Laboratory.

504. Ames Laboratory, Ames, Iowa. **Electrical properties of magnesium silicide and magnesium germanide,** by C. R. WHITSETT and G. C. DANIELSON. n.p., Jly. 1955. (AEC Rept. ISC-714).

Single crystals of Mg_2Si and Mg_2Ge obtained and measurements made of electrical resistivities and Hall coefficient between 60–1000°K. Both compounds behaved typically as excess impurity semiconductors and exhibited intrinsic conditions above 450°K.

505. AMIRKHANOV, K. I., BAGDUEV, G. B. and KAZHLAEV, N. A. **Anisotropy of thermal conductivity in a tellurium monocrystal.** *Akad. Nauk. SSSR. Dok.* **124**: 554–556, Jan. 1959.

In Russian.

Cites the results of thermal conductivity measurements for monocrystalline tellurium. A strongly manifested anisotropy of the thermal conductivity is present in the direction of the crystallographic axis of the monocrystal; this anisotropy decreases as the temperature increases. Thus, at a temperature of 100°K, $\lambda \parallel$ (the coefficient of thermal conductivity for a flux directed along the cleavage plane) is more than twice the value of $\lambda \perp$ (the coefficient of thermal conductivity for a heat flux directed perpendicular to the cleavage plane). At 500°K, $\lambda \parallel$ is 1·5 times the value of $\lambda \perp$.

506. AMIRKHANOV, K. I. *et al.* **The effect of phonon dragging on thermomagnetic phenomena in bismuth selenide.** *Akad. Nauk. SSSR. Dok.* **117**: 781–784, Dec. 1957.

In Russian.

Translation in Infosearch Tech. Lit. Info. Serv. Russian Lit Survey SEM-5-58, p. 12·1–12·5.

Measurements were made of the electrical conductivity, Hall effect, thermal emf, and transverse and longitudinal Nernst-Ettingshausen effect in polycrystalline Bi_2Se_3 specimens with the aim of establishing the influence of phonon dragging.

507. ANDERSON, J. S. and GREENWOOD, N. N. **The semiconducting properties of cuprous oxide.** *Roy. Soc. London Proc.* **215**: 353–370, Dec. 5, 1952.

A procedure is described for preparing reproducable specimens of Cu_2O at the oxygen-poor limit of its composition range. Measurements of the electrical conductivity and thermoelectric power of such specimens are reported for the temperature range 20–1030°C. The curves for both properties consist of two sections, the discontinuity occurring at 355°C in both cases. Below this temperature the thermoelectric power has a constant value; at higher temperatures it decreases and remains characteristic of a positive-hole conductor up to the highest temperatures used. The effect of added oxygen was investigated; the theoretical implications of the results obtained are discussed.

508. ANDREW, A. and DAVIDSON, C. R. **Induced thermoelectric potential from radiation damage.** *Phys. Rev.* **89**: 876, Feb. 15, 1953.

Letter. It is shown that bombardment of 0·005 in. iron and constantan wires by 10 MeV protons increases the thermoemf's considerably. Annealing the specimens at successively higher temperatures restores the original values.

509. ANDREWAITHA, G. G. and EVANS, E. J. **Hall effect and some other physical constants of alloys—the copper-tin series of alloys.** *Phil. Mag.* **31**: 265–282, 1941.

The thermoelectric power of copper-tin alloys with respect to copper varies with composition between +1 and −3 microvolts per degree centigrade.

510. ANDREWS, J. P. **Thermoelectric power of cadmium oxide.** *Phys. Soc. Proc.* **59**: 990–998, Nov. 1957.

The thermoelectric emf (E) against Pt was measured over a temperature range of −110° to 800°C. The results above 100°C are well represented by the formula $E = -aT + b \log_e T - C$, in which the values of the constants A, b, and c vary somewhat according to the previous treatment of the specimen; their values in a number of different experiments are given; their mean values are a=0·154, b=3·43, and c=225 (E in mV). The results are discussed, and if it is assumed that the number of conduction electrons is given by $n = Be^{-B/KT}$, B is found to be 0·034 eV. The sign of the thermoelectric power indicates that CdO is an excess conductor. (*Sci. Abs.* **51A**: 332, 1948).

511. ANNAEV, R. G. **Anomalous variation of the thermo-emf of Ni-Mn alloys in a magnetic field.** *Akad. Nauk. SSSR. Dok.* **63**: 639–640, June 1948.

In Russian.

The longitudinal and transverse Thomson effect was studied in Ni–Mn alloys. The observations of the effect on pure Ni and on the alloy of 5 at.% Mn agreed perfectly with the second law of Akulov (Ferromagnetism, Moscow, 1939) whereas in the other cases anomalies were observed (shown in 3 graphs). These may be explained theoretically by considering higher terms in the series expressing Akulov's second law, and physically by the occurrence of a para-process. (*Sci. Abs.* **52A**: 6211, 1949).

512. ANNAEV, R. G. and KOLODIN, M. V. **Measurement of the electrical resistance and thermoelectric emf of the alloy Fe_3Pt in longitudinal**

and transverse magnetic fields. *Akad. Nauk. SSSR. Dok.* **87**: 195–196, 1953.

In Russian.

"The experiments reported earlier have been extended to show that heat treatment of the alloy can give an ordered or non-ordered system each of which has different electrical properties. When heated to 1000°C and quenched in water the longitudinal and transverse galvanomagnetic effects are of different sign, the transverse being the larger and negative. The two thermomagnetic effects are of the same positive sign in weak fields but in powerful fields the transverse changes sign and becomes negative up to 9000 oersteds when it again becomes positive. After annealing at 650°C for 100 hr and quenching in air, the signs of the longitudinal and transverse galvanomagnetic effects are still the same but the longitudinal effect is reduced. The two thermomagnetic effects are of different sign, the longitudinal becoming positive, the transverse again remaining negative up to 9000 oersteds when it changes sign." *Sci. Abs.* **57A**: 2421, 1954.

513. ANNAEV, R. G. and YAZLIEV, S. **Investigation of the variation of the thermoelectromotive force of nickel-palladium alloys in longitudinal and transverse magnetic fields.** 8 p., figs., Washington, D.C., *U.S. Naval Research Laboratory*, 1959 (Trans. 760).

Translation of article from *Izvestiya Akademii Nauk. Turkmenskoi SSR.* **6**: 3–8, 9157.

For original entry, see Item 14, May 1959 issue.

513. ANNAEV, R. G., and YAZLIEV, S. **The thermoelectromotive force of nickel-palladium alloys in longitudinal and transverse magnetic fields.** *Akad. Nauk. Turkmen. SSSR. Izvest. no.* 6, p. 3–8, 1957.

In Russian.

"The alloys investigated contained 0–100% Ni, and were studied at concn. intervals of 10%. The alloys were tempered, and the transverse and longitudinal thermomagnetic effects were investigated. The law of anosotropy of even effects was verified. The effect of the paramagnetic process on the curves of the thermomagnetic effect was found in the exprts. At the stoichiometric compn. $NiPd_3$ the curves for the thermomagnetic effect have a mix. which must be explained on the basis of a superstructure." *Chem. Abs.* **52**: 11498, Jly. 25, 1958.

514. ANTELL, G. R., CHASMAR, R. P., CHAMPNESS, C. H. and COHEN, E. **The electrical properties of indium arsenide and indium antimonide.** "Semiconductor Meeting Report," p. 99–107, *Phys. Soc.* 1957.

"Details are given of the method of preparation and purification of the compound InAs. Measurements have been made of Hall coefficient, electrical conductivity and thermoelectric power between room temperature and 500°C for pure specimens and for samples doped with Zn and with Se. It is concluded from the values of thermoelectric power that some degree of degeneracy exists even in pure specimens with the temperature range considered. Making correction for this degeneracy a value for the energy gap at 0°K of 0·50 eV is obtained." *Sci. Abs.* **60A**: 7987, 1957.

515. ARAFA, A. A., SHAFIE, I. S., and SULTAN, F. S. A. **Measurement of the thermoelectric power of lead sulphide.** *Z. Angew. Math. u.Phys.* **7**: 256–264, May 25, 1956.

Measurements on natural specimens of PbS over the temperature range between room temperature and 700 K are reported. Specimens originally of n-type remain so; with specimens originally of p-type the thermoelectric power changes sign at a temperature within the range. Differences of behaviour between the specimens are discussed; one crystal exhibited metallic conduction and an extraordinarily large thermoelectric power.

516. Arizona State University, Tucson, Ariz. **Thermoelectric materials and device research.** 17 p., Dec. 17, 1959. (Quart. Prog. Rept. 1) (Contract DA 36-039-sc-85249).

In this report, the previous knowledge concerning the thermal and electrical properties of rutile which would make it useful as a thermoelectric material are briefly discussed. A modification of the material which might improve the thermoelectric figure of merit is proposed. Experimental efforts to produce rutile in a suitable form by the treatment of colloidal precipitates is described.

517. Armour Research Foundation, Chicago. Ill. **Method of purification of metals and intermetallic compounds,** by SHERMAN SUSMAN. 83 p., illus., June 1959. (WADC Tech. Rept. 59–303). (Contract AF 33(616)–5895).

The physical and chemical properties of the silicon carbide, thorium oxide and zirconium oxide systems are considered in the context of diffusion phenomena and thermoelectric behaviour at elevated temperatures.

519. ARON, ANDRE. **Force electromotrice et pouvoir thermoelectrique du couple aluminium-argent. (Electromotive force and thermoelectric power of the aluminium-silver couple).** *Acad. Sci. Paris. Compt. Rend.* **240**: 852–853, Feb. 21, 1955.

In French.

Preparation by vaporisation, in vacuo, of pure Ag and pure Al, in relatively thick deposits, with an electric resistance near 1Ω.

520. ARON, ANDRE. **Juxtaposition thermocouples in thin deposits.** *Acad. Sci. Paris. Compt. Rend.* **245**: 48–50, 1957.

In French.

Describes experiments in which one element is Al or Ag and the other a semiconductor (Cu_2O, Te, Sb oxide) superimposed over an Al or Ag deposit. A simple and remarkable result was obtained by the couple Ag/Al superimposed by Cu_2O. At the start the thermoelectric power was

constant, indicating action by the Al/Ag couple only. The power rose rapidly above 300°C. The potential vs. current curve deviated from Ohms' law. Similar, but more complex phenomena occurred with Al/Ag coated by Te. The instability of the phenomenon and return to state near the initial state in the case of Cu_2O are excluding the assumptions of ordinary modifications of electric properties of Al by the diffusion of oxide. A real effect of juxtaposition seems to occur on the whole length of contact of the semiconductor with the metal on which it is deposited.

521. ARON, ANDRE. **Thermoelectricite des lames minces metalliques. (Thermoelectricity of thin metallic films).** *Algiers Univ. Pub. Sci. Ser.* **B4**: 33–46, 1958.

The thermoelectric power of the following couples of metals and alloys is given: Ag–Al, Te–Al, Al–Bi, Sb–Al, Sb–Ag, SbAg–Al, SbAl–Sb, SbZn–Bi, SbZn–C, BiTeSb–BiTe.

522. ARON, ANDRE. **Variation of thermoelectric power of an aluminium/silver couple by modification of the hot soldering under the effect of a chemical reaction or by the introduction of conductors or semiconductors.** *J. Phys. et Radium.* **17**: 287–289, Mar. 1956.

In French.

The thermoelectric power from the thermocouple silver/aluminium used in comparatively thick films, is equal to 5·45 microvolts/degree between 150° and 380°C. It is increased if the hot soldering is eroded by iodine or if a thin layer of antimony is introduced between the silver and aluminium. The erosion by bromine or the interposition of conductors or semiconductors provides a variable increase: the thermoelectric power changes then in direct ratio with the rise in temperature. (*Sci. Abs.* **59A**: 6661, 1956).

523. ASANABE, SIZUO. **Electrical properties of Stannous selenide.** *Phys. Soc. Japan. J.* **14**: 281–296, illus., Mar. 1959.

The electrical resistivity, Hall coefficient and thermoelectric power were investigated over the temperature range from 100—800°K on pure and impurity-doped SnSe crystals. An anomalous hump of the Hall coefficient was found to occur at about 200°C in most of the as-grown crystals and this seems to make the conventional analysis based on a simple semiconductor model impossible. Anisotropies in the resistivity and Hall coefficient were also studied on single crystals and the observed anisotropy in the resistivity seems to be ascribed to an anisotropy in the effective mass of holes. Hole mobility varies at $T^{-2.0}$ at high temperatures and its discrepancy from $T^{-1.5}$ law is explained on the assumption of both optical and acoustical mode scatterings. Further investigation was made of the anomalous Hall coefficient on heating the specimen at various temperatures in vacuum. This anomalous phenomenon was found to depend on the heat-treatment history of the crystal and the experimental results were analysed on such a simple model that acceptors are introduced into SnSe by impurity diffusion above 200°C and caused to disappear on heating at lower temperatures. General features observed seem to be in fair agreement with the proposed model.

524. ARVIN, M. J. **Thermoelectric effects in molybdenum disilicide.** *J. Appl. Phys.* **24**: 498. Apr. 1953.

Letter. Further evidence for the metallic nature of $MoSi_2$ is given; in particular, its thermal emf against Pt, in the temperature range −60° to 600°C, is much the same as that of Cu against Pt.

525. BARANSKII, P. I. and KONOPLYASOVA, N. S. **Study of volume-gradient thermal emf and thermal conductivity in monocrystals of germanium with known crystallographic orientation.** *Sov. Phys. Tech. Phys.* **2**: 1493–1501, Aug. 1958.

Translation of paper appearing in *Zhurn. Tekh. Fiz.* **28**: 1621–1630, Aug. 1958.

The volume-gradient of the thermo-emf developed in the volume heterogeneities of germanium was studied. The temperature processes of the thermoelectrical forces and the isotropic thermal conductivity of germanium monocrystals were determined.

526. BARRIE, R., CUNNEL, F. A., EDMOND, J. T. and ROSS, I. M. **Some properties of gallium Arsenide.** *Physica.* **20**: 1087–1090, 1954.

Paper at Amsterdam Conference on semiconductors.

Specimens of GaAs, prepared by heating the elements together in stoichiometric ratio, were all n-type, minimum carrier density, $2{\cdot}5 \times 10^{17}$ cm^{-3}. Turnover voltages at a point contact ranged from 10 to 150V. Optical, data give an energy gap of 1·35 eV, compared with 1·25 eV from photoconductivity measurements. An effective mass ratio for electrons of 0·03 is deduced from thermoelectric data.

527. BARRIE, R. and EDMOND, J. T. **A study of the conduction band of Insb.** *J. Electron.* **1**: 161–170, Sept. 1955.

Measurements of optical absorption edge, thermoelectric power, Hall coefficient and conductivity are made on a wide range of specimens. Analysis of the results suggests that the conduction band is not parabolic.

528. BASHIROV, R. I. **Investigation of the Nernst-Ettingshausen effect in bismuth telluride.** *Soviet Phys. Tech. Phys.* **3**: 917–920, May 1958.

Translation of article in *Zhurn. Tekh. Fiz.* **28**: 986–989. May. 1958.

The Nernst–Ettingshausen effect, electrical conductivity and Hall effect were measured potentiometrically at 120–600 K. The results throw light on the state and behaviour of current carriers in Bi_2Te_3.

529. BASHSHALIEV, A. A. and ABDULLAEV, G. B. **Effect of bromine on the electrical conductivity of**

selenium. *Izvest. Akad. Nauk. Azerbaidzhan SSR. no.* **2**: 3–11, 1957.

In Russian.

"The experiments were carried out at 20–100° with Se contg. 0·016–0·13% Br. The hole cond. of Se and growth of cond. rate and emf with temp. increase with the content of Br. In the presence of 0·13% Br the emf is twice that of the pure Se. The relation of cond. and temp. can be expressed by the empirical equation $\sigma = \sigma_0 e^{-E/2kT}$ where E is energy of hole dissocn. E decreases from 0·36 to 0·13 e V with increasing Br. The increase of cond. below 40° is related mostly to the increase of carrier mobility and above 40° to the increase of carriers concn. The change of mobility, depending on the content of Br, rises up to 3100 times at 30°." *Chem. Abs.* **51**: 12639, 1957.

530. Batelle Memorial Institute, Columbus, Ohio. **The electrical properties of uranium oxides,** by R. K. WILLARDSON, J. W. MOODY, and H. L. GOERING. 41 p., Sept. 25, 1956. (Rpt. 1135).

The electrical conductivity and thermoelectric power of uranium oxides in the UO_2–U_3O_7 range have been studied at temperatures between 27° and 400°C after annealing at 200°, 400°, 600°, 800°, and 1000°C.

531. Batelle Memorial Institute, Columbus Ohio. **Thermoelectric power generation and related phenomena.** 11 p., illus., Dec. 21, 1959. (Bimon. Prog. Rept. 6) (Contract Nobs-77034) (AD 231575)

The preparation and characterisation of AlAs-GaAs alloys are continuing with several different methods of preparation being investigated. Construction is virtually completed on the apparatus for electrical high-temperature measurements and well along on the thermal-diffusivity apparatus. No experimental work was done on the fundamental-properties investigation as activity was confined to a literature survey.

532. Batelle Memorial Institute. Columbus, Ohio. **Thermoelectric power generation and related phenomena.** 15 p., Feb. 26, 1960. (Bimon. Prog. Rept. 7) (Nobs-77034).

The materials development effort was directed toward (1) preparation of alloy ingots of GaAs-AlAs of low aluminium content ($\leq$ 10 mole percent AlAs) by the zone-levelling technique, using induction heating, and by the normal freeze technique, using resistance heating; (2) determination of a suitable container for the preparation of AlAs; and (3) testing of the high-temperature-measurement apparatus. In addition, the thermal-gradient crystal-growth technique was applied to the preparation of the alloy from a GaAl-solution. Selected specimens were studied by X-ray diffraction, metallographic examination, hardness determinations, and chemical analyses to determine composition and the degree of homogeneity.

533. Batelle Memorial Institute, Columbus, Ohio. **Thermoelectric properties of Bi_2Te_3-Bi_2Se_3 alloys,** by R. T. BATE. 9 p., Mar. 15, 1960. (Tech. Rept. 3) (Nonr-2316(00)).

Electrical resistivity, thermoelectric power and thermal conductivity were measured in the temperature range between 68°K and room temperature. The figure of merit was determined from the difference between adiabatic and isothermal resistivity measurements.

This report constitutes the text of a talk given before the American Physical Society in Cleveland on November 27, 1959. An abstract appears in *Am. Phys. Soc. Bull.* **4**: 409, Nov. 27, 1959 with authors W. C. MYERS and R. T. BATE listed.

534. BAYNTON, P. L., RAWSON, H. and STANWORTH, J. E. **Semiconducting properties of some vanadate glasses.** *Electrochem. Soc. J.* **104**: 237–240, Apr. 1957.

Study of BaO–V_2O_5–P_2O_5 and Na_2O–BaO–V_2O_5–P_2O_5 systems with V_2O_5 between 50 and 87 mol. %. The glasses were semiconductors; those with highest V_2O_5 have spec. cond. of the order of 10^{-5}/ohm-c. at room temperature. Relation between spec. cond. and temperature was determined. Conductivity values obtained could be easily reproduced and were not sensitive to variations in melting conditions.

535. BENEL, H. **Copper layers which nullify the thermoelectric electromotive force of a thin silver/massive silver monometallic couple.** *Rev. Fac. Sci. Univ. Istanbul.* **22C**: 117–123, 1957.

In French.

The thermoelectric emf of the monometallic couple, thin Ag/massive Ag, can be cancelled by a Cu coating on the massive Ag branch. The thickness of Cu needed depends on the temperature and the thickness of the thin Ag branch.

536. BENEL, H. **Study of the thermoelectromotive force of unimetallic (thin Ag/thick Ag) and bimetallic (thin Ag/thick Cu or thick Ag/thin Cu) couples as a function of the thickness of the thick branches.** *Rev. Fac. Sci. Univ. Istanbul.* **21C**: 261–271, 1956.

In French.

"The thermal emf E of a thick Ag/thin Ag (I) and a thick Ag/thin Cu (II) couple was measured between 100° and 300°. E varies with the thickness (d) of the thin branch and is independent of d of the thick branch provided d is greater than 200 m/μ.

537. BENEL, H. **Thermal emf of a couple (thin film of Cu in contact with solid Ag). Variation with layer thickness.** *Rev. Fac. Sci. Univ. Istanbul.* **19C**: 162–168, Apr. 1954.

In French.

Measurements made on thin films deposited and measured in the same vacuum system, thereby preventing the oxidation previously caused by removing from the system for measurement. The thermal emf decreases as the layer thickness increases and only reaches its limiting value for thicker crystalline layers.

538. BENEL, H. **Thermoelectric couples made of several chemically different layers.** *Rev. Fac. Sci. Univ. Istanbul.* **21C**: 272–276, 1956.

In French.

The thermo-emf E of a couple made up of thick Ag (I) and thin Ag (II) increases when alternate layers of Ag and Cu are deposited on the thin branch. The effect of the so-created inhomogeneities is additive. If a layer of Cu is deposited on I the value of E can be reduced to zero. The thickness of Cu depends on the thickness of II. If II is 70 mμ, then Cu has to be 17-40 mμ thick to make E negligibly small or zero in the temperature range of 28–170°.

539. BENEL, H. **Thermoelectric emf in a monometallic circuit.** *Rev. Fac. Sci. Univ. Istanbul.* **18A**: 65–78, Jan. 1953.

In French.

Thermoelectric emf's due to inhomogeneity in the orientation of the metallic crystals, or to occluded gases, disappeared in time and could be removed by heating, but emf due to heterogeneity in geometrical form remained. The existence of emf's in absence of all such heterogeneity was not definitely established.

540. BENEL, H. **Thermoelectric properties of antimony telluride and solid solutions of Sb_2Te_3-Bi_2Te_3.** *Acad. Sci. Paris. Compt. Rend.* **247**: 584–587, Aug. 4, 1958.

In French.

In the system Sb-Te there was an increase of the thermoelectric power α and resistivity p with Te concentration. The solid solutions, Sb_2Te_3-Bi_2Te_3, are of the p type as their constituents.

541. BHATIA, A. B. **On the electrical properties of cold worked iron carbon alloys,** *Phys. Soc. Proc.* **62B**: 229–237, Apr. 1, 1949.

The change on "ageing" in the electrical properties of cold worked Fe-C alloys of low concentration is investigated theoretically.

542. BHATIA, A. B., and MACDONALD, D. K. C. **On the thermoelectric power of dilute metallic alloys.** *Can. J. Phys.* **34**: 419–422, Apr. 1956.

The quantity $\delta \log p_0/\delta \log E$ where p_0 is the resistivity of a metal due to impurities and imperfections and E is the Fermi energy, is discussed. By choosing the correct form for the potential of an impurity ion the possible range of values of $\delta \log p_0/\delta \log E$ is much increased.

543. BIDWELL, C. C. **Thermal electromotive forces in oxides.** *Phys. Rev.* **3**: 204, 1914.

Thermocouples of tin, iron, chromium, tungsten, cadmium, zinc, lead and their oxides yield electromotive forces as high as 1·5 volts with a temperature difference of 80° ∝.

544. BIDWELL, SHELFORD. **On a relation between the coefficient of the Thomson effect and other physical properties of metals.** *Roy. Soc. London Proc.* **37**: 25–28, 1884.

The Thomson thermoelectric coefficient is correlated with resistance, specific heat, and expansion of the various metals considered.

545. BIRKHOLZ, ULRICH. **Investigation of the intermetallic compound bismuth telluride and its solid solutions with antimony and selenium regarding their applicability as materials for semiconductor thermal elements.** *Z. Naturforsch.* **13a**: 780–792, 1958.

In German.

"Addition of AgI to Bi_2Te_3 gave an n-type semiconducting material. A p-type material was also produced with the optimum compn. $Bi_{0.6}Sb_{1.4}Te_3$. Such materials, in conjunction gave a thermoelectric effectiveness of $2{\cdot}1 \times 10^{-4}$/degrees, equiv. to a Peltier cooling of 80°. Powder metallurgical studies resulted in the production of a series of similar materials whose properties were also examined. Noteworthy was a reduction in the lattice thermal conductivity of these materials, compensated by a drop in the mobility, and a reduction in the deflect-electron concn. The elements were tested in vacuo at 10^{-3} mm. and a critical Peltier cooling of 80° was observed-Contact resistance was reduced by use of ultra. sonic techniques in order to permit these measurements." *Chem. Abs.* **53**: 5879, 1959.

546. BITLER, W. R., YANG, LING and DERGE, G. **Measurement of the thermoelectric power of a molten FeS-solid tungsten thermocouple.** *J. Appl. Phys.* **28**: 514–515, Apr. 1957.

Several measurements made with △ T's of 100 to 150°C. in the 1150 to 1400°C. range. Thermoelectric power is approximately 55 microv./°C. in this range, compared with 35·6 microv./°C. for chromelalumel and 12 microv./°C. for Pt-PtRh.

547. BLACK, J., CONWELL, E. M., SEIGLE, L. and SPENCER, C. W. **Electrical and optical properties of some $M_2^{V\text{-}B}N_3^{VI\text{-}B}$ semiconductors.** *Phys. & Chem. Solids*, **2**: 240–251, 1957.

The above was synthesized as single crystals of fairly good purity. Resistivity, thermoelectric power, infrared transmission, and in some cases Hall effect were measured in order to characterise these compounds as semiconductors.

548. BLOEM, J., KROGER, F. A. and VINK, H. J. **The physical chemistry of lead sulfide in relation to its semiconducting properties.** *In* Defects in Crystalline Solids, Bristol, 0. 273–282.

The semiconducting properties of lead sulfide single crystals have been measured after heating at various temperatures in controlled atmospheres. Thermoelectric power measurements indicate an energy gap of 0·3 eV at room temperature, and an effective electron and hole mass of about 0·25 of the electron mass in free space. With the use of the theory of Kröger, Vink and van den Boomgaard it was possible to deduce the width of the energy gap and the position of the various vacancy levels as a function of temperature, from 800° to 1200°K.

549. BLUE, M. D. and DANIELSON, G. C. **Electrical properties of arc-evaporated carbon films.** *J. Appl. Phys.* **28**: 583–586, 1957.

Uniform thin films of carbon in the thickness

range 100 to 2300 A have been prepared by arc-evaporation in vacuum. The values of the resistivity, temperature coefficient of resistivity and thermoelectric power of the annealed films were in agreement with the corresponding values for ordinary fine-particle carbon blacks. Other properties and applications of the films are discussed.

550. BLUM, A. I. **Electrical properties of solid solutions of Te-Se.** *Zhurn. Tekh. Fiz.* **23**: 788–795, 1953.

In Russian.

Experimental study of electrical conductivity, Hall effect, and thermo-emf of solid solutions of Te-Se with Se from 0–15 wt. % in the temperature range 30 to −190° C. With low Se (to 2%), the electrical conductivity, thermo-emf and concentration curves show anomalous forms. For a more thorough treatment of the results in this region, a detailed X-ray study is necessary.

551. BLUM, A. I. and REGEL', A. R. **Issledovanie termoeds splavov tellura i selena v tverdom i zhidkim sostoyaniii. (Investigation of thermo-emf of liquid tellurium and of liquid and solid selenium).** *Zhurn. Tekh. Fiz.* **23**: 783–787, figs., May, 1953.

In Russian.

Report of an experimental study of the effect of temperature on the thermo-emf of Te and two of its alloys with Se (85% Te+15% Se; 30% Te+70% Se) in the temperature range from 100 to 500°. A diagram of the apparatus is provided. The experiments showed that, for melts of Te and its alloys with Se, the thermo-emf decreased. This confirms the idea of the increase of the metallic character of the bonds in these alloys during their melting.

552. BLUM, I. and REGEL, A. R. **Electric properties of solid solutions of mercury-selenide and selenium.** *Zhurn. Tekh. Fiz.* **21**: 316–327, Mar. 1951.

In Russian.

Electric conductivity of HgSe with small additions of Se was measured in the range of temperatures from −190°C to 850°C. The Hall effect and differential thermoelectromotive force were measured between −180° and 280°C. These measurements have shown the melting point of HgSe to be 690 ± 10°C. Limited solubility of selenium in hard HgSe was established.

553. BODINE, J. H., JR. **Hall coefficient and thermoelectric power of thorium metal.** *Phys. Rev.* **102**: 1459, June 15, 1956.

Measurement of Hall coefficient of thorium at room temperature in magnetic fields of about 4000 gauss giving average of $-1{\cdot}2\times10^{-11}$ volt-cm./abampere gauss: emf curve of Th-Pt thermocouple in range 400 to 1100°C.

554. BOGORODITSKII, N. P., PASYNKOV, V. V., KHOLUYANOV, G. F. and YAS'KOV, D. A. **Electrical properties and uses of silicon carbide.** *Akad. Nauk. SSSR. Ser. Fiz. Izvest.* **20**: 1571–1580, 1956.

In Russian.

Translation in *Acad. Sci. USSSR. Bull. Phys. Ser.* **20**: 1440–1447, 1956.

A review of properties, uses and possibilities.

555. BOLTAKS, B. I. and MOKHOV, YU. N. **Diffusion of lead in lead telluride.** *Zhurn. Tekh. Fiz.* **26**: 2448–2450, 1956.

In Russian.

English translation appears in *Sov. Phys. Tech. Phys.* **1**: 1266–2368, 1956.

Concerns an investigation of the coefficients of diffusion for various impurities in lead telluride.

556. BOLTAKS, B. I. **The diffusion of antimony and tin in semiconductors composed of SbZn.** *Akad. Nauk. SSSR. Dok.* **100**: 901–903, 1955.

In Russian.

Diffusion coefficients of Sb and Sn in SbZn were determined by using Sb^{124} and Sn^{113} in experiments made over 40 to 60 hours at temperatures of 317 to 477°C. Graph indicates that for each metal the increase in log coefficient with temperatures is linear to 400°; above 400° the two rates are also linear but have much steeper slopes. At all points the coefficient for Sn is 5 to 10 times as great as for Sb.

557. BOLTAKS, B. I., MATVEEV, O. A. and SAVINOV, V. P. **Electric properties of zinc telluride.** *Zhurn. Tekh. Fiz.* **25**: 2097–2103, 1955.

In Russian.

Measurements were made with ZnTe of stoichiometric composition with 1% Te excess, and with 1% Se as impurity. The compounds were prepared at 1300%, and the measurements were made with samples of $3\times6\times15$ mm. The resistivity was measured from room temperature up to 600°. The pure compound shows a distinct break in the log σ vs. 1/T (°K) curve; for the two branches the activation energy of the carrier current is $0{\cdot}24\pm0{\cdot}03$ and $0{\cdot}65\pm0{\cdot}03$ e.v., respectively. The coefficient of the thermal emf has a maximum at about 600° for the pure sample, the one with Te excess did not show a maximum, but the one with Se showed two maximums. The amount of holes (lattice disturbances) was measured from room temperature to 220° and also the mobility thereof (carrier current). The curves for the three materials go more or less parallel to each other.

Translation available from LC or SLA (Tech. Trans. **2(12)**: 896, Dec. 18, 1959.

558. BOLTAKS, B. I., VASENIN, F. I. and SALUNINA, A. E. **Electric and thermoelectric properties of partially reduced (blue) titanium dioxide.** *Zhurn. Tekh. Fiz.* **21**: 532–546, 1951.

In Russian.

Translation MDF-B-134 available from Friedman.

Specific conductivity of TiO_2 increases with time of reduction. All samples show electronic conductivity; ionic was not detected. The temperature coefficient of conductivity is positive. Increase in reducing time of TiO_2 decreases the coefficient of thermal emf. In slightly reduced samples this coefficient decreases—in strongly reduced samples

it slowly increases—with increase in temperature. Hall effect was not measurable. Dissociation energy of current carriers follow a law showing for other semiconductors determining temperature variation of conductivity. High effective mass of current carriers in TiO_2 explains the relatively high value of thermal emf and low conductivity. Effective mass of these current carriers in TiO_2 can several times exceed the mass of a free electron.

559. BOLTAKS, B. I., and TARNOVSKI, N. N. **Electrical characteristics of chalcopyrite. The effect of surface treatment on the rectifying properties of crystals.** *Zhurn. Tekh. Fiz.* **25**: 402–409, Mar. 1955.

In Russian.

Experiments were conducted over a wide range of temperatures to determine the electric and thermoelectric properties of natural and synthetic $CuFeS_2$. The temperature dependence of the electrical conductivity of these materials is of a more complex character than in ordinary impurity semiconductors. By etching the surface it is possible to considerably improve the rectifying properties of the crystals and in a number of cases to obtain static characteristics not inferior to those of Ge and Si detectors.

560. BOLTAKS, B. I. and PI-KHUAN, TSZYAN. **Izmerenie koeffitsienta termo-eds tellura s primesiami medi i sur'mi pri perekhodi ot tverdogo k zhidkomu sostianiya. (Variation of the thermal emf coefficient of Te containing Cu and Sb on transition from the solid into the liquid state).** *Zhurn. Tekh. Fiz.* **28**: 222–224, Jan. 1958.

In Russian.

Translation in *Sov. Phys. Tech. Phys.* **3**: 197–199, Jan. 1958. Also in Infosearch Tech. Lit. Info Serv. Russian Lit. Survey SEM-5-58, p. 7·1–7·3.

This coefficient has been measured for Te containing up to 1 wt. % Cu or Sb up to temperatures of ~ 600°C. The addition of impurities makes it possible to vary the thermal emf between solid and liquid Te.

561. BOLTAKS, B. I. and MOKHOV, U. N. **Samodiffuziya i diffuziya primesie v telluride i selenide svintsa. (Self diffusion and diffusion of impurities in lead telluride and lead selenide).** *Zhurn. Tekh. Fiz.* **28**: 1046–1050, May 1958.

In Russian.

Translation in Infosearch Tech. Lit. Info Serv. Russian Lit. Survey SEM-5-58, p. 5·1–5·5.

Data on the diffusion of Te, Sn and Sb in PbTe and of Se and Sb in PbSe are reported.

562. BOLTAKS, B. I. and ZHUZE, V. P. **Physical properties of intermetallic compounds of constant composition. (On the mechanism of conductivity of Mg_3Sb_2).** *Zhurn. Tekh. Fiz.* **18**: 1459–1477, Dec. 1948.

In Russian.

A general survey is given of presentday knowledge of the nature of bonds in intermetallic compounds. Electrical conductivity and variation of electrical conductivity with temperature, Hall effect, thermoelectric force and thermal conductivity are experimentally determined for the system Mg-Sb in the neighbourhood of the stoichiometric point Mg_3Sb_2. It is concluded that Mg_3Sb_2 is a typical representative of a phase of constant composition and according to its electrical properties appears to be an alloyed semiconductor.

563. BORELIUS, G., KEESOM, W. H., JOHANSSON C. H. and LINDE, J. O. **Measurements on thermoelectric forces down to temperatures obtainable with liquid helium.** *Ned. Akad. Wetens. Proc.* **35**: 25–33, figs., 1932.

Thermoelectric forces against a silver alloy-normal were measured down to the temperatures which are obtainable with liquid helium, for Pt and for alloys of Cu with small quantities of Fe.

For the last-mentioned alloys the thermoelectric force per degree near absolute zero is proportional to T. At increasing temperatures e reaches a maximum after which e decreases. With increasing concentration of Fe this maximum is displaced towards higher temperatures.

As a sensitive thermoelement for the temperature range of liquid hydrogen and liquid helium the authors recommend the combination Au with about 1 at. % Co. against Ag with about 1 at. % Au.

564. BORELIUS, G., KEESOM, W. H. ,JOHANSSON, C. H. and LINDE, J. O. **Measurements on thermoelectric forces down to temperatures obtainable with liquid or solid hydrogen.** *Ned. Akad. Wetens. Proc.* **35**: 15–24, figs., 1932.

Thermoelectric forces against a silveralloy-normal were measured down to the temperatures obtainable with liquid or solid hydrogen for Ag and an alloy of Ag with Au and for Au with small quantities of Fe, Co, Ni, Mn, Cr or Ti respectively.

565. BORELIUS, G., KEESOM, W. H., JOHANSSON, C. H. and LINDE, J. O. **Measurements of thermoelectric forces of lead and tin down to the temperature of liquid helium.** *Ned. Akad. Wetens. Proc.* **34**: 1365–1371, illus., 1931.

Thermoelectric forces per degree were measured, for lead down to 1·7°K, for tin down to 4·8°K, in both cases against a silver-alloy wire. The authors conclude from those measurements that the thermoelectric force per degree for a couple supraconducting lead-silver-alloy is small. From their measurements on the combination lead-tin together with Meissner's statement they admit that the thermoelectric force for supraconducting lead-supraconducting tin is zero. For both metals there is a rapid change in de/dT and hence in the Thomson-heat at the temperatures where the metals become superconductive. The authors conclude that the Thomson-effect at the critical temperature rapidly falls from finite values to zero.

566. BORELIUS, G. **Thermoelectricity at low temperatures.** *Physica*, **19**: 807–814, graphs., Sept. 1953.

Several investigations have been made on thermoelectric, resistometric and magnetic properties of various metals and alloys.

567. BOWERS, R., BAUERLE, J. E. and CORNISH, J. **Some electrical and thermal properties of $InAs_{1-x}P_x$.** *Am. Phys. Soc. Bull.* **4**: 134, Mar. 30, 1959.

Abstract only.

Measurements have been made between 350 C and 800 C of the electrical resistivity, the Seebeck coefficient (thermoelectric power) and the thermal conductivity of n-type $InAs_{1-x}P_x$, with x varied from 0 to 0·4. These measurements extend earlier data of Weiss to higher temperatures. On the whole, results agree with reasonable extrapolations of the data of Weiss, except at $x=0$, where somewhat higher Seebeck coefficients are obtained. The electrical properties of these alloys show qualitatively a similar temperature dependence to those of InAs, but the magnitude of the resistivity and Seebeck coefficient increase with increasing x in the intrinsic range because the addition of phosphorus increases the energy gap. The thermal conductivity data exhibits a sum of 1/T behaviour due to the phonon-phonon scattering and a temperature independent contribution due to phonons scattered by the phosphorus added. No anomalous behaviour of the thermal conductivity was found at high temperatures. The value of this ternary system for thermoelectric power generation is discussed.

568. BOWERS, R., URE, R. W., JR., BAUERLE, J. E. and CORNISH, A. J. **InAs and InSb as thermoelectric materials.** *J. Appl. Phys.* **30**: 930–934, illus., June 1959.

Measurements of the electrical conductivity, thermal conductivity, and Seebeck coefficient (thermoelectric power) of InSb and InAs have been made at high temperatures. The thermoelectric figure of merit averaged $0{\cdot}42\times10^{-3}$ °K^{-1} between 100 and 500°C for InSb and $0{\cdot}44\times10^{-3}$ °K^{-1} between 500 and 750°C for InAs. Hence n-InAs and InSb in series may be used to generate electrical power with an efficiency of about 6% when used in conjunction with p-type materials of similar characteristics. In neither InSb up to 500° nor InAs up to 800°C did the thermal conductivity show the large high-temperature anomaly previously reported in InSb.

569. BOWERS, R., BAUERLE, J. E. and CORNISH, A. J. **$InAs_{1-x}P_x$ as a thermoelectric material.** *J. Appl. Phys.* **30**: 1050–1054, illus., Jly. 1959.

Measurements of the electrical conductivity σ, the thermal conductivity K, and the Seebeck coefficient (thermoelectric power) α, of $InAs_{1-x}P_x$ have been made at high temperatures with x varying from 0 to 0·4. Between 450° and 800°C, the average thermoelectric figure of merit ($z=\alpha^2\sigma/K$) increases moderately with x for small values of x, reaching a maximum near $x=0{\cdot}1$, and subsequently decreasing. Between 450 and 800°C, the average z for $x=0{\cdot}1$ is equal to $0{\cdot}63\times10^{-3}$ (°K)$^{-1}$, a 15% improvement over InAs. For the same figure of merit, the Seebeck coefficient and the electric resistivity is higher in the ternary than in the binary InAs; this is advantageous for the design of thermoelectric devices. Previous values for the thermoelectric figure of merit of InAs are revised.

570. BOWLEY, A. E., DELVES, R. and GOLDSMID, H. J. **Magnetothermal resistance and magnetothermoelectric effects in bismuth telluride.** *Phys. Soc. Proc.* **72A**: 401–410, Sept. 1958.

The magnetothermal resistance and magnetothermoelectric effects have been measured for samples of p-type and n-type Bi_2Te_3 at 77°K. Scattering laws for the charge carriers have been derived from the magnetothermoelectric effect and also from the magnetothermal resistance effect for p-type material. It has, however, not been possible to fit a simple scattering law to the results from the magnetothermal resistance effect in n-type material.

571. BRADY, E. L. **Preparation and properties of lead telluride.** *Electrochem. Soc. J.* **101**: 466–473, Sept. 1954.

Investigation of electrical properties and chemical stability of PbTe; single crystals of PbTe prepared, and resistivity and Hall coefficients determined; both n- and p-type PbTe were produced but they were not of high resistivity.

572. BROPHY, J. J. **Seebeck effect fluctuations in germanium.** *Phys. Rev.* **111**: 1050–1052, figs., Aug. 15, 1958.

Fluctuations in the Seebeck effect or thermoelectric power of germanium single crystals have been observed. The Seebeck noise power spectrum varies as reciprocal frequency and may be quantitatively predicted from current-noise measurements. Carrier density fluctuations responsible for 1/f noise are also the source of Seebeck noise. The present results indicate that carrier fluctuations having a 1/f spectrum persist even in the absence of net d.c. current flow. Seebeck noise is also observed in low-noise specimens having nonohmic, noisy electrodes.

573. BUSCH, G. **Electron conduction in nonmetals.** *Z. Agnew, Math. u Phys.* **1**: 81–110, 1950.

In German.

Continuation of a previous publication dealing in particular with the conductive mechanism in Cu_2O, SiC, Si and oxides with spinel structure. The activation energy of many semiconductors is found to be a function of their impurity content. An interpretation of this relation is proposed which takes account of the energy necessary for the production of lattice defects. The relation between activation energy and dielectric constant of the lattice is also discussed, as is the effect of mechanical pressure on the conductivity. Experimental and theoretical results on the thermoelectric properties of semiconductors are surveyed, with special references to NiO and SiC.

574. BUSCH, G., HULLIGER, F. and WILKLER, U. **Electrical conductivity and thermopotential in the intermetallic compound Mg_3Sb_2.** *Helv. Phys. Acta.* **27**: 195–196, 1954.

A polycrystalline sample of the α-form was prepared by melting the components in an atmosphere of argon. Its electrical conductivity, Hall effect, and thermopotential was determined from room temperature to 1000°K. The width of the forbidden zone was 0·82 eV. Both the Hall constant and the differential thermopotential have a positive sign over the whole temperature range. The compound is thus an anomalous semiconductor and the mobility of holes is greater than that of electrons. Concentration, mobility and degrees of freedom were calculated for both holes and electrons.

575. BUSCH, G., HULLIGER, F. and WINKLER, U. **Electrical properties of the intermetallic compound Mg_3Sb_2.** *Helv. Phys. Acta.* **27**: 249–258, June 30, 1954.

In German.

Measurements were made of the conductivity, Hall coefficient and thermoelectric voltage of a polycrystalline specimen of the α-phase compound, obtained by melting the components together, over a range of temperatures. The width of the forbidden energy band is found to be 0·82 eV. Hall coefficient and thermoelectric voltage both have positive signs up to very high temperatures; this is interpreted as indicating that the mobilities of the holes are greater than those of the electrons. The concentrations, mobilities and availability coefficients of electrons and holes are determined from the measurements.

576. BUSCH, G., WIELAND, J. and ZOLLER, H. **Electronic properties of gray tin.** *In* Semiconducting Materials, p. 188–197, London, Butterworth Sci. Publs. 1951.

Hall effect and the change of resistivity in a magnetic field have been measured by conventional methods with special precautions. The Hall coefficients are found to increase rapidly with decreasing temperature. Remarkably high changes of the resistivity in magnetic fields have been observed. Large thermoelectric emf's are generated at a junction of gray and white Sn. The experiments show that gray tin is a semiconductor of high electrical conductivity and properties very similar to Si and Ge.

577. BUSCH, G., SCHMID, P. and SPONDLIN, R. **Thermovoltages between silicon carbide, copper and platinum.** *Helv. Phys. Acta.* **20**: 461–463, 1947.

In German.

Measurements of thermoelectric power were carried out between 75°K and 1000°K. Green and black specimens of SiC were found to give thermoemf's of opposite sign, in accordance with the different nature of their impurity centres. The thermoelectric power increases almost linearly with increasing absolute temperatures, more rapidly for black SiC than for the green variety. The existence of a positive correlation between thermoelectric power and activation energy was confirmed.

578. California University, Minerals Research Laboratory, Berkeley, Calif. **Chemical considerations in high temperature thermoelectric power development,** by A. W. SEARCY and D. J. MESCHI. 32 p., Mar. 1959. (Tech Rept. 6, Ser. 84, Issue 6) (Contract Nonr-222(32)) (AD 214 711).

Solid semiconductors which may be suitable for use at temperatures higher than 1500°K are the subject of this paper. The first section contains a brief analysis of the relationship between intrinsic band gap and chemical composition. Then limitations placed on high temperature use of various semiconductor materials by their physical and chemical properties are discussed.

579. CARASSO, J. I. and PITTMAN, R. W. **Thermoelectric observations on grey selenium.** *Nature* **182**: 1011, Oct. 11, 1958.

Reports some thermoelectric results, obtained in the course of an investigation of the photocatalytic properties of this modification of selenium which are at variance both with common experience and with the models of Henisch and Francois.

580. CARLSON, R. I. **Electrical properties of mercury telluride.** *Phys. Rev.* **111**: 476–478, 1958.

On preparation in sealed quartz tubes, polycrystalline p HgTe results, with acceptor concentrations of $10^{18\text{-}19}$/cc. and band gap of approximately 0·0002 eV. By diffusion, Zn enters as a donor, and Cu as an acceptor impurity. Resistivity and Hall effect measurements down to liquid-H temperature must show magneto-Hall effect. The Hall coefficient changes sign as low as 20°K. Some measurements were made of thermal conductivity and of thermoelectric power.

581. CATTERALL, J. A. **The electronic structure of palladium-uranium alloys.** *Phil. Mag.* **2**: 491–498, Apr. 1957.

The measured effects of uranium upon the paramagnetic, susceptibility, electrical resistivity, thermoelectric power and lattice parameter of palladium are discussed, and an interpretation of the results in terms of a solvent and solute band is suggested.

582. CHANDRASEKHAR, B. S. **The Seebeck coefficient of bismuth single crystals.** *Phys. & Chem. Solids.* **11**: 268–273, Oct. 1959.

The Seebeck coefficient S of single crystals of bismuth has been measured between room temperature and about 250°C. The results are used to resolve a discrepancy in the data on the Seebeck coefficient of polycrystalline bismuth as given by Sato and Savournin and Poggi; the values given by the latter workers are shown to be more reasonable. The anisotropy in S at 300°K is analysed in terms of the current model for the carriers in bismuth. Abeles and Meiboom's results from magnetoresistance measurements and

the present data are used to calculate the density-of-states effective masses of the electrons and holes respectively. The value for the electrons agrees well with that deduced from de Haas–van Alphen effect and cyclotron-resonance experiments. The value for the holes is very close to that deduced from cyclotron resonance, but much smaller than is suggested by electronic heat-capacity data.

583. CHAPLIN, R., CHAPMAN, P. R. and GRIFFITH, R. H. **Electrical properties of chromium-oxide-alumina catalysts.** *Nature* **172**: 78, Jly, 11, 1953.

Letter. The catalyst (I) of 70% Cr_2O_3 and 30% Al_2O_3 was compressed into a thin disc, and both its conductivity k and its thermoelectric potential θ were measured by a condenser method. The behaviour of k in O_2 and H_2 shows I to be an amphoteric semiconductor, and that of θ shows I to be an electron-excess semiconductor. The Hall coefficient was also measured. It is suggested that the method offers considerable promise for examining mixed catalysts.

584. CHAPMAN, P. R., GRIFFITH, R. H. and MARSH, J. D. F. **The physical properties of chromium oxide-aluminium oxide catalysts. II. Electrical properties.** *Roy. Soc. London. Proc.* **224A**: 419–426, 1954.

The electrical conductivity and thermoelectric potential was measured for co-precipitated Cr_2O_3–Al_2O_3 catalysts.

585. CHARNOCK, H. and YEO, S. A. **Thermoelectric emf of tin-cadmium alloys.** *J. Sci. Instr.* **36**: 478–479, Nov. 1959.

In seeking a solder which has little or no thermoelectric emf's to copper, measurements were made of Cd, Sn, and Cd/Sn alloys relative to Cu, in range 0–80°C. The values of the constants a and b for each alloy, together with other data appear in a table.

The alloys with high cadmium content melt about 200°C and all can be used as solders with only a little more care than the usual Pb/Sn alloy. A typical lead/tin solder (60Pb/40Sn) was found to have the same thermoelectric emf as pure tin.

586. CHASMAR, R. P. and STRATTON, R. **Effective electron mass in indium arsenide and indium antimonide.** *Phys. Rev.* **102**: 1686–1687, June 15, 1956.

Reports measurements made of Hall coefficient and thermoelectric power at room temperature and above. Values of thermoelectric power indicated that both materials were slightly degenerate at all temperatures within the range considered.

587. CHERPAKOV, V. P. **Thermal and electrical conductivity of compounds of Bi with Sn.** *Moskov. Univ. Ser. Mat. Mekhan. Astron. i Fiz. Khim. Vestnik. no.* 3, 129–134, 1957.

In Russian.

Studies of thermoelectric force.

"The alloys investigated consisted of a number of possible mixtures from Bi 100% to Sn 100%, and the changes with temperature of the thermal conductivity, the electrical conductivity, the thermal emf, and the Wiedeman-Franz ratio were investigated in the range from room temperature to the melting point of the alloys. It was found that in pure Bi and in Bi+Sn, just as observed for Bi+Pb earlier (Mikryukov and Tyapumina) the electrical conductivity is due in part to electrons, and in part to holes (lattice disturbances).

588. CIRKLER, F. **The anisotropy of the absolute thermoelectric emf of tin between 0° and 280°C.** *Z. Naturforsch.* **8a**: 646–659, Oct. 1953.

In German.

The preparation and measurement of the emf's against Pt 10% Rh, of eight single crystals of orientations 11-1/2-86° and one polycrystal are described in detail. The apparatus is shown schematically. The single-crystal rods were 15–25 cm long and were prepared by seeding and slow cooling from the melt. The variation with temperature, t, of the emf's is shown graphically and expressions in the form $at+bt+ct^3$ are derived for the emf's and absolute emf's, e. The anisotropy $(e_{11}-e_{\perp})/e_{450}$ is 4% at the melting point and the change in thermoelectric power 1·6μV/deg. C. The results are compared with those of previous investigators. The theories of Sommerfeld-Bethe and Kohler on the dependence of emf on purity and orientation are discussed and it is shown that the author's results deviate more from Voight's $\cos^2$ law than the theories suggest.

589. CHRISTIAN, J. W., JAN, J. P., PEARSON, W. B. and TEMPLETON, I. M. **Thermoelectricity at low temperatures. VI. A redetermination of the absolute scale of thermoelectric power of lead.** *Roy. Soc. London, Proc.* **245A**: 213–221, charts, June 3, 1958.

The writers have determined the absolute thermoelectric power of zone-purified lead up to 18°K by direct measurement against the superconductor Nb_3Sn.

599. CHRISTY, R. W., FUKUSHIMA, E. and LI, H. T. **Thermoelectric power of silver bromide containing cadmium bromide.** *J. Chem. Phys.* **30**: 136–138, 1959.

Measurements were made at 100–400 on pure AgBr and on AgBr containing $CdBr_2$ in concentrations between 0·01 and 1·0 mole %. Satisfactory agreement was observed with the theory of Howard and Lidiard, (see Item 242, June 1959 issue) if it was assumed that the heats of transport were temperature dependent. The values required for the sum of the heats of transport of the interstitial Ag ions and vacancies were −0·57 eV. at 175° and −0·69 eV. at 250°.

591. CLARK, H. and BERETS, D. J. **Vanadium oxides as oxidation catalysts: electrical properties.** *In* Advances in Catalysis v. 9, p. 204–214, 1957.

V_2O_5 powder, pellets, and thin films have been used in making measurements of the thermoelectric emf, the d.c. electric resistance, and the a.c. electric resistance. It is concluded that O vacancies in the crystal lattice form electron donor levels 0·42 eV. below the conduction bands and are in sufficient concentration to be a good source of

electrons for the solid. The defects appear to be mobile in the surface region below 180°, but in the bulk only above 350°. The concentration of defects at the surface is greatly diminished by chemisorbed O, which causes the formation of a surface barrier layer. The presence of an electron-donating agent such as ethylene or xylene prevents the formation of the barrier layer.

592. CLEAVES, H. E. and DAHL, A. I. **Thermal electromotive force of uranium against platinum.** *In* U.S. Atomic Energy Commission TID 5290, Book I, p. 364–371, 1958.

The thermal emf of U against Pt increases regularly with increasing temperature from 0 mV at 0° to 25·5 mv. at 900°. The data are given in graphic and tabular form for five lots of U for which the analytical data are listed.

593. COBLENZ, ABRAHAM. **Semiconductor compounds open new horizons.** *Electron.* **30**: 144–149, Nov. 1957.

Comprehensive survey of semiconducting compounds with discussion of their characteristics, unusual properties, and applications, present and future. Tables of intermetallic and dye semiconducting compounds summarize presently available data on these materials.

594. COLES, B. R. **Electronic structures and physical properties in the alloy systems—nickel-copper and palladium-silver.** *Phys. Soc. Proc.* **65B**: 221–229, Mar. 1952.

A comparison is made of the magnetic, electrical and thermoelectric properties of alloys in the two systems, and the lattice spacings, optical properties electronic specific heat and X-ray spectroscopy of the Ni-Cu alloys are also considered.

595. Compagnie Generale de Telegraphie San Fil, Puteaux, France. **A preparation and study of compounds of the II-IV type and mixtures thereof to determine their useful semiconducting properties.** 1 April to 30 June, 1959. 24 p., illus., 1959. (Quart. Tech. State Rept. 1) (Contract AF 61 (052) 243). (AD 229 775).

Research was concentrated on the design and fabrication of equipment for preparation and purification of materials, establishment of phase diagrams, and electrical and thermoelectrical measurements. A research programme in thermoelectric power conversion was initiated by study of the thermal and electronic properties of solid solutions of semiconducting crystals.

596. COOPER, H., SCHWED, P. and WEBELER, R. W. **Thermoelectric power of AuCu in nonequilibrium states.** *J. Appl. Phys.* **27**: 516–518, May 1956.

Measurements of resistivity and of TE power (Q) versus Pt of samples of AuCu in various nonequilibrium states; one set of samples was disordered by quenching from 750°C and annealing curves were obtained at 100, 149, 198, and 258°C; second set was first ordered, then cold worked to essentially complete disorder, and annealing curves taken at 149 and 258°C.

597. CORNISH, A. J. **Arrays of inorganic semiconducting compounds.** *In* Westinghouse Research Laboratories, Pittsburgh, Pa. Thermoelectricity Progress Report 12. 18 p., illus., Jan. 1959.

Arrays of compounds related to the periodic chart of the elements can be prepared. These arrays aid in estimating the physical and chemical properties of compounds, including semiconducting properties. Many compounds included in the arrays may not exist; however, if the compound does exist the value of its melting point, energy gap and electron mobility generally fits into a uniform pattern related to adjacent compounds. The crystal structure of semiconducting compounds is shown to be of only second-order importance, grouping semiconducting compounds by crystal types loses overall relations that exist between many compounds.

598. CORRUCCINI, R. J. **Annealing of platinum for thermometry.** *J. Res.* **47**: 94–103, Aug. 1951.

Experiments are described on the annealing of Pt wire in which the coefficient of resistance and thermal electromotive force were used as criteria of the physical state of the metal. Contrary to predictions the Cu and Ag alloys were thermoelectrically positive to Pt at ordinary temperatures. Thus far, no impurity other than Au has been found to lower the thermoelectric power of Pt. It is apparently not possible to represent the kinetics of annealing in terms of a temperature activated process having a single value of activation energy. This result is interpreted in terms of the diffusion of dislocations.

599. COSTA, P. **Determination du pouvoir thermo-electri-ue de l'uranium et du plutonium. (Determination of thermoelectric power of uranium and plutonium.)** *J. Nuclear Mat.* **2**: 75–80, Mar. 1960.

The thermoelectric power of uranium and plutonium have been measured by a differential method. In agreement with previous measurements by Waldron and Lee, a high value of thermoelectric power has been found for the α and *B* phases of plutonium, and a low value for the σ and ε phases, particularly the σ. This last result rules out Varley's explanation for the negative thermal expansion coefficient of the *B* phase. The observed variation of the thermoelectric power with temperature is slightly different from that reported by Waldron and Lee.

600. CRAWFORD, J. H., JR. and WILLIAMS, F. E. **Electronic processes in zinc fluoride and in the manganese-activated zinc fluoride phosphor.** *J. Chem. Phys.* **18**: 775–780, June 1950.

Measurements have been made of the temperature dependence of electrical conductivity and thermal emf on ZnF_2 and ZnF_2: Mn, and of the Hall coefficient and rectifying power at 25°C on ZnF_2. Both ZnF_2 and ZnF_2:Mn are n-type impurity semiconductors. The presence of MnG_2 in

ZnF_2 decreases the electronic conductivity by a factor of about 10^3, indicating a decrease in the concentration of electron donors by oxidation. A marked dependence of the temperature variation of conductivity on heat treatment has been observed. Contrary to the simple theory, the absolute values of the thermal emf increase with temperature. From the Hall coefficient and conductance at 25°C of heat-treated ZnF_2, a concentration of free electrons of 3×10^{16} cm^{-3} and a mean free path of $6{\cdot}7 \times 10^{-8}$ cm are deduced. ZnF_2 rectifies in the expected direction.

601. CROATTO, V. **Thermoelectric power and lattice disorder in semiconductors.** (*La*) *Ricerca Sci.* **19**: 1324–1326, 1949.

Not examined.

"Measurements were made of the thermoelectric power between two samples of the same semiconductor with different degree of lattice disorder. The substances investigated were CdO and CoO, and their lattice disorder could be varied by varying the oxygen pressure in the atmosphere in which the samples were maintained. CdO has a defect of O, and is therefore an n-type semiconductor due to the presence of F-centers; its conductivity is reduced on increasing the pressure. CoO has instead an excess of oxygen, is p-type, and its conductivity increases on increasing the gaseous oxygen pressure. Besides confirming these views on the nature of conduction in these oxides, results proved the validity of the theoretical formula $dE/dT = \pm(R/F) \log (\sigma_1/\sigma_2)$, where the $+$ sign applied to n-type conductors, R is the gas constant, F the Faraday equivalent, σ_1 and σ_2 the conductivities of the two samples." *Sci. Abs.* **53A**: 4071, 1950.

602. CRUSSARD, C. and AUBERTIN, F. **The variation of the thermoelectric power of metals with dissolved elements.** *Acad. Sci. Paris. Compt. Rend.* **226**: 1003–1005, Mar. 22, 1948.

In French.

The thermoelectric power at 20°C of several Al alloys, formed by the addition of a known quantity of either Sn, Si, Ti, Cr, Mn, Fe, Ni, Cu or Mg to 99·995% Al, relative to Al, have been measured. The alloys were produced in two ways: by quenching from 600°C, and by slow cooling over a period of 48 hours. The power for the slowly cooled alloy is never > that for the quenched. The results, together with those to be found in the literature for other bases, confirm that, with a few exceptions, the dissolved element increases or decreases the thermoelectric power of the base according as the element is to the left or right of the base in the 8 column periodic table.

603. CULLITY, B. D., TELKES, M. and NORTON, J. T. **Electrical resistivity and thermoelectric power of antimony-selenium alloys.** *J. Metals* **2**: 47–52, tables, Jan. 1950.

This research was initiated in an attempt to find a material for use in thermoelectric generators and although none of the antimony-selenium alloys is suitable for this purpose, the properties of Sb_2Se_3 indicate that it may have applications as a thermistor material.

604. CULLITY, B. D. **The thermoelectric properties and electrical conductivity of bismuth-selenium alloys.** *Metals Tech.* **15**: No. 1, Tech. Pub. 2313, 8 p., Jan. 1948.

Unlike most other systems, the Bi-Se system has no maximum in TE power and electrical resistivity at the compn. of the intermediate phases. The only binary alloys suitable for use in TE generators contain about 37% Se. The TE efficiency is about 6% after correcting for avoidable losses when tested against a Zn–Sb alloy containing additive agents. Further improvement in the properties of an alloy containing about 37% Se can be obtained by the addition of small amounts of Te.

605. CUSACK, N. and KENDALL, P. **A note on the viscosity and resistivity of liquid gallium.** *Phys. Soc. Proc.* **75**: 309–311, Feb. 1, 1960.

Thermoelectric power of liquid gallium relative to chromel and alumel were measured and results are indicated in a table.

606. CZANDERNA, A. W. and HONIG, J. M. **The composition, resistivity and thermoelectric power of cerium oxides below 500°C.** *Phys. & Chem. Solids* **6**: 96–97, figs., Jly. 1958.

Letter to the editor presenting some findings on the stoichiometry, resistivity, and thermoelectric power of ceria, in high vacuum and in oxygen, for the temperature range 25–485°C.

607. DAHL, A. I. and VAN DUSEN, M. S. **Resistance-temperature relation and thermoelectric properties of uranium.** *J. Res.* **39**: 53–58, Jly. 1947.

The paper describes measurements made on the resistance-temperature relation and the thermoelectric properties of several samples of uranium. The resistance-temperature relation showed sharp breaks at about 650° and 770°C, indicating the existence of transformation points. The very rapid changes in resistance occurred at a somewhat higher temperature on heating than on cooling. Only slight irregularities in the thermoelectric properties were noted in the region of the transformation points.

608. DAS, J. N. **Study of the semiconducting properties of pyrolusite.** *Z. Physik.* **151**: 345–350, May 8, 1958.

In German.

Electrical conductivity has been determined over a temperature range 300 to 500°K and an expression is given for its variation with temperature over this range. The current-voltage characteristics of metal point semiconductor contacts are non-linear symmetrical curves. The Hall constant yields carrier concentration as $4{\cdot}3 \times 10^{19}$/cm.3 and mobility as $1{\cdot}2$ cm^2 $volt^{-1}$ $second^{-1}$. Specimens develop a thermoelectric power of 200μ V/K to 500 μ V/K which is fairly constant over the range 300 to 800°K. The sign of the thermo-emf and of

the Hall constant indicate that the specimens are "n" type.

609. DE FAGET DE CASTELJAU, P. and FRIEDEL, J. **Study of the resistivity and thermoelectric power of dissolved impurities in the noble metals.** *J. Phys. et Radium* **17**: 27–32, Jan. 1956.

In French.

The diffusion of a free electron gas by a spherical potential well of fixed radius and variable depth is investigated theoretically. For weak potentials the model developed accounts very satisfactorily for polyvalent impurities dissolved in the noble metals. Resonance effects associated with bound levels such as 2p, 3d, and so on produce larger potentials and enable the effects of transition metals in the noble metals to be investigated.

610. DE NOBEL, D. **Phase equilibria and semiconducting properties of cadmium telluride.** *Philips Res. Rep.* **14**: 361–399; 430–492, Aug., Oct. 1959.

Experimental results are first given regarding preparation, phase diagram, Hall effect and specific resistance as a function of the temperature, Hall effect as a function of the atmosphere over the crystals at various values of the temperature, thermoelectric power, photoconductivity and luminescence; later, these results are interpreted.

611. DEVYATKOVA, E. D. **Issledovanie teplonrovodnosti telluristogo svintsa. (Investigation of the thermal conductivity of lead telluride.)** *Zhurn. Tekh. Fiz.* **27**: 461–466, Mar. 1957.

In Russian. Translation in Infosearch Tech. Info. Serv. Semiconduction Applications. Russian Lit. Survey SEM–3–57, p. 3·1–3·7, June 1957.

Studies made on material that could be used in the production of thermoelectric batteries. Investigates the possible mechanisms of heat conductivity in semiconductors.

612. DEVYATKOVA, E. D., MASLAKOVETS, YU. P. and STIL'BANS, L. S. **On the thermal and electrical conductivities and the thermoelectric force of Sb/Zn alloys, with special reference to the influence of small admixtures of other metals.** *Zhurn. Tekh. Fiz.* **22**: 129–142, Jan. 1952.

In Russian.

The authors investigated the variations of the electrical and thermal conductivities and of the Hall constant of Sb/Zn alloys with the proportions in the neighbourhood of the metallic compounds, and also the influence of the admixturés of small quantities of Ag, Cd, In, Sn, and Te. They attach considerable importance to the role which the admixtures can play by dissolving the impurities of the components of the alloy and improving the lattice that way.

613. DEWALD, J. F. and LE·OUTRE, G. **The thermoelectric properties of metal-ammonia solutions. I. The thermoelectric power of sodium and potassium at −33°.** *Am. Chem. Soc. J.* **76**: 3369–3376, Jly. 5, 1954.

The thermoelectric properties of sodium and potassium solutions in liquid ammonia at −33° have been studied over the concentration range from 0·002 M to saturation. Experimental procedures are outlined, with particular emphasis on methods of preparing solutions of maximum stability. The data for the concentrated solutions are shown to be in strikingly good accord with the predictions based on a degenerate electron gas model. In the dilute range of concentration, where one ordinarily expects the best agreement between theory and experiment, a marked anomaly is observed. The thermoelectric power increases with dilution almost exactly twice as rapidly as theory predicts it should.

614. DEVYATKOVA, E. D., MASLAKOVETS, YU. P., STIL'BANS, L. S. and STAVITSKAYA, T. S. **Temperature dependence of the mobility of the carriers of electricity in semiconductors.** *Akad. Nauk. SSSR. Dok.* **84**: 681–682, 1952.

In Russian.

In contrast to the theoretical formula for the temperature dependence of mobility, $u=AT^{-3/2}$ for solids with an atomic lattice (at temperatures high enough that electron scattering by lattice defects is negligible), which was verified for Si, Ge, and Sb–Zn, the theoretical formula for solids with an ionic lattice, $u=AT^{1/2}$ (above the Debye temperature 0) has never been verified experimentally. Measurements of electric conductivity and Hall effect of PbSe between 20 and 500°C gave the experimental result $u=AT^{-3}$, entirely out of line with the theoretical formulas. By comparison of the melting points, heats of fusion, and heats of formation of PbSe and PbS ((N) about 50°K) it appears certain that foı PbSe, (N) is well below 50° and, consequently, the temperature range studied is well above (N). An analogous temperature dependence of u was also found by Zhuse, by recalculation of the experimental data of Busch, Wieland, and Zoller for gray tin. This discrepacny makes a radical revision of the theory of interaction of electrons with the thermal lattice vibrations imperative.

615. DEVYATKOVA, E. D., MASLAKOVETS, YU. P. and SOMINSKII, M. S. **The thermoelectric effect in lead sulfide.** *Akad. Nauk. SSSR. Ser. Fiz. Izvest.* **5**: 409–416, 1941.

In Russian.

Theoretical expressions are given for the dependence of thermo-emf on carrier concentration. The temperature variations of electric and thermal conductivities and of TE force are investigated in PbS having electronic as well as hole conductivity. Results indicate that in PbS the carrier concentration is 10^{18} to 10^{19}. The electric conductivity is determined mainly by the temperature variation of the mobility of the carriers.

616. DOMENICALI, C. A. **Thermoelectric power and resistivity of solid and liquid germanium in the vicinity of its melting point.** *J. Appl. Phys.* **28**: 749–753, Jly. 1957.

The thermoelectric power of Ge against Pt was measured between room temperature and 1030°C. The resistivity of Ge decreases by a factor of approximately 19 upon melting, and is approximately 63 microhm-cm. in the liquid phase.

617. DONOVAN, B. and REICHENBAUM, G. **Electrical properties of chalcopyrite.** *Brit. J. Appl. Phys.* **9**: 474–477, Dec. 1958.

Conductivity σ and thermoelectric power ϕ of synthetic and natural specimens were investigated in the temperature range −140° to 300°C.

618. DOWLING, P, H. **The contact potential between the solid and liquid phases of bismuth.** *Phys. Rev.* **31**: 244–250, Feb. 1928.

Relation between thermoelectric power and temperature change at contact potential is discussed.

619. DRUYVESTEYN, M. J. and BLOK VAN LEAR, K. J. **Thermoelectric power of cold-worked copper at low temperature.** *Nature* **173**: 591, Mar. 27, 1954.

Reports measurements at room temperature, on copper and silver wires.

620. DRUYVESTEYN, M. J. and MENSEN, H. **Thermoelectric power of cold-worked silver and gold wires at low temperatures.** *Appl. Sci. Res.* **4B**: 388–392, 1955.

Results of measurements of thermoelectric power of couples consisting of drawn and annealed gold and silver wires respectively.

621. DUDKIN, L. D. and ABRIKOSOV, N. K. **A study of the effect of nickel on the properties of the semiconducting compound $CoSb_3$.** *Zhurn. Neorg. Khim.* **2**: 212–221, 1957.

In Russian.

"In order to investigate the limits of the solid soln. based on $CoSb_3$ and the nature of its relationship to other phases, an isothermal section (at 540°C) was constructed of the ternary Co-Ni-Sb system up to 50% Sb. A narrow range of ε solid soln. based on $CoSb_3$ was found; its composition can be represented as (Co, Ni) Sb_{3-x}, where x = 0–0·5, while the amount of Co replaced by Ni varies from 0 to ~ 10%. The results of thermoelec. measurements and X-ray phase analysis, as well as microscopical evidence, confirm the existence of this solid-solution region. Microhardness measurements of ε-phase alloys across a section of const. Sb content show the absence of ternary chem. compounds in this region. Detn. of the phys. properties of $CoSb_3$ alloyed with Ni indicate that the Ni gives rise to donor impurity levels which are fully ionized at room temp. A marked increase in the mobility of electrons takes place on the replacement of 0·5 at % Co by Ni. It is suggested that this phenomenon is related to the removal of defects and the distortion of the ε-phase lattice by the soln. of small amounts of Ni. The lattice thermal conductivity of $CoSb_3$ falls linearly with increase in the number of Co atoms replaced by Ni. From thermo-elec. measurements it is established that the bonds in the compounds NiSb and $NiSb_2$ are predominantly metallic." *Metall. Abs.* **25**: 501, Mar. 1958.

622. DUDKIN, L. D. and ABRIKOSOV, N. K. **Study of the thermoelectric properties of cobalt antimonides.** *In* Problems of the Metallurgy and Physics of Semiconductors, Proceedings, Second Conference on Semiconductor Materials. p. 97–109. Moscow, Academy of Sciences, USSSR. 1957.

In Russian. Translated by M. Friedman, noted in *Trans. Mon.* **4**: 264, June 1958.

"The starting materials used in this investigation were twice-distilled antimony containing less than 0·01% Pb and As and a somewhat higher Si content, and cobalt powder, obtained from cobalt nitrate, containing about 0·3% impurities. Specimens were prepared by melting the components in corundum crucibles under spectrographically pure flux and casting in moulds. The Co-Sb system was studied for Sb concentrations above 50%. A phase diagram of this range of concentration was constructed on the basis of thermal analysis and the variation of electrical resistivity of the specimens with temperature was investigated. An X-ray analysis of the compound $CoSb_3$ was carried out. The effect of the presence of nickel was examined. The compound $CoSb_3$ appears to be a chemical compound of semiconductor type with a wide forbidden zone." Lib. Bull. Adm. Centre Sci. Inform. and Liaison. Roy. Nav. Sci. Serv. p. 60, May 1958.

623. DUDKIN, L. D. and ABRIKOSOV, N. K. **Alloying of the semiconductive compound cobalt antimonide.** *Fiz. Tverdogo Tela* **1**: 142–145, 1959.

In Russian. Trans. In *Soviet Phys. Solid State* **1**: 126–133, Jan. 1959.

The ε phase $CoSb_3$ is a semiconductor with a specific conductivity of 10 to 30 ohm^{-1} cm^{-1} and a thermal emf varying from −200 to 30 microvolts/degree depending on the deviation from stoichiometry (excess Sb leads to conduction by holes). Alloys with 0·5% Cu, Zn, Al, Ti, Fe, Ni, Si, Ge, Sn, Pb, Bi, Se, and Te were prepared. Only Fe, Ni, Bi, Sn, and Te affected the electronic properties of the ε phase and their effects were studied as a function of concentration. Addition to Ni and Te increases the n-type conductivity σ and the thermal emf α while decreasing the thermal conductivity. Fe brings about an increase in σ and causes complicated changes in the magnitude and sign of the thermoelectric power as a function of concentration. Bi decreases the thermal conductivity but does not affect appreciably other properties. Sn changes the conductivity to p-type. Graphs of the temperature dependence of α and σ are given and the phenomena are explained in terms of charges and sizes of the substituent atoms.

624. DUDKIN, L. D. and ABRIKOSOV, N. K. **Physicochemical study of the cobalt antimonides.** *Zhurn. Neorg. Khim.* **1**: 2096–2105, 1956.

In Russian.

The Co-Sb system was studied by X-ray and thermal analysis and the microstructure and

physical properties (electric conductivity, thermal emf, and heat conductivity) were determined. A new cobalt antimonide was found, $CoSb_3$ (ε-phase) which is formed at 859° by a peritectic reaction. This compound is cubic-body centred, space group Th^5. The Sb-Sb, Co-Sb bonds in the crystal lattice are covalent. The values of the thermal electric properties show that the compound CoSb has a predominantly metallic nature. The compounds $CoSb_2$ (δ-phase) and $CoSb_3$ are semiconductors.

625. Dudkin, L. D. and Ostranitsa, A. P. **Ternary semiconducting compounds $A^IB^VB^{VI}$.** *Akad. Nauk. SSSR. Dok.* **124**: 94–97, Jan. 1, 1959.

In Russian.

Four compounds were studied: $Cu\text{-}SbSe_2$, $AgSbSe_2$, $AgSbTe_2$, and $AgBiSe_2$, with melting points at 472, 634, 561 and 792°C, respectively. ($AgBiSe_2$ showed a polymorphic transformation at 298°C). Electrical and thermal conductivity, thermoelectric power and microhardness were measured. Thermal activation energies were (in e.v.): $AgSbSe_2$, 0·58; $CuSbSe_2$, 0·16 and 0·80; $AgBiSe_2$, 0·34 (low temperature form) and 0·10 (high temperature form). A chemical bonding scheme is suggested in which A^{I+} ions are situated in a covalently bonded (B^V-B^{VI}) structure.

626. Dudley, L. P. **Thermoelectric couples.** *Elec. Rev.* **127**: 243–244, 1940.

Thermoelectromotive forces are given for several metals at various temperatures.

627. Dedmond, J. T., Broom, R. F. and Cunnell, F. A. **The properties of callium arsenide.** "Semiconductor Meeting Report," p. 109–117, Phys. Soc. 1957.

"The purification of gallium, arsenic and gallium arsenide are described. Measurement of Hall effect and conductivity over a range of temperature from 1·4K to 700°C have shown some interesting effects. The highest figures for mobility ($R_H\sigma$) obtained are 4680 cm^2 sec^{-1} $volt^{-1}$ for electrons and 340 for holes at 20°C. For lattice scattering μ_h is approximately proportional to T^{-2} but the variation of μ_e is uncer'ain. Impurity band conduction in p-type gallium arsenide has been observed. Thermoelectric power measurements yield a value of $m_h^* = 0{\cdot}5\ m_o$ and $m_e^* = 0{\cdot}06\ m_o$ approximately at room temperature. Magneto-resistance measurements are given for certain crystal orientations, field strengths, and directions of field." *Sci. Abs.* **60A**: 7898, 1957.

628. Egli, P. H. **Thermoelectric power generation.** *In* Electro-Optical Systems, Inc. Proceedings of a Seminar on Advanced Energy Sources and Conversion Techniques, Pasadena, California, 3–7 November 1958, vol. **1**, p. 83–94, figs., Pasadena, Calif. 1958. (Contract DA-36-039-SC-78064) AD 209301; PB 151461.

Discussion of difficulties inherent in the development of materials.

629. Ehrenreich, H. **Transport of electrons in intrinsic indium antimonide.** *Phys. & Chem. Solids* **9**: 129–148, 1959.

The calculated mobility and thermoelectric power for the effective ionic charge determined from optical experiments, agree well with experiment.

630. Ekkers, G. J., Farner, A. and Klaui, R. **Thomson coefficient of some metals at high temperatures.** *Helv. Phys. Acta* **21**: 218–219, 1948.

In German.

Measurements of the Thomson coefficient were made with W (up to 2700°K), Mo (900–2200°K) and Pt (1200–1700°K). By means of a disappearing filament pyrometer temperatures were measured along wires consisting virtually of two wires of different diameter. Theoretical values (Sommerfeld) for the Thomson coefficient, assuming one free electron per one atom, are given by $-1{\cdot}2 \times 10^{-8}$VT/deg K (V=voltage), the observed values being: W, 0·93, Mo, 1·05; Pt, 1·05, instead of 1·2.

631. Elpat'evskaya, O. D. and Regel', A. R. **Concerning some possibilities of measuring the intensity of hall emf film transducers made of HgSe, HgTe, or their solid solutions.** *Zhurn. Tekh. Fiz.* **26**: 2432–2438, Nov. 1956.

In Russian.

Mercuric selenide and mercuric selenide-mercuric telluride are suitable materials for film transducers to measure the Hall electromotive force which indicates the intensity of the magnetic field. The sensitivity of these transducers approaches that of germanium and indium antimonide. (*Rev. Met. Lit.* **14**: 74–P, 1957.)

632. Elpat'evskaya, O. D. **Electrical properties of thin layers in the system HgSe-HgTe.** *Zhurn. Tekh. Fiz.* **28**: 2676–2683, 1958.

In Russian.

Electrical conductivity (σ), thermoelectric power (α) and Hall effect were studied in the range −200° to 100°C for layers evaporated on to mica or glass. Layers rich in HgSe showed extremely small variation of σ with temperature, unlike those rich in HgTe. The highest α values were obtained for the latter (~120 μV/deg). Mobilities approached those for single crystals, at room temperature but tended to saturate at low temperatures. Comparison was made between this behaviour and that for compressed powders and specimens grown from the melt, to investigate the effect of crystal size. Sensitive Hall probes were prepared which showed negligible variation of Hall emf over the range −200° to 80°C.

633. Emel'yanenko, O. V. and Nasledov, D. N. **The electrical properties of gallium arsenide at low temperatures.** *Zhurn. Tekh. Fiz.* **28**: 1177–1187, June 1958.

In Russian.

Measurements were made on the Hall constant, electrical conductivity, and transverse magnetoresistance from 1·5 to 300°K; the thermoelectric power was also measured from 120–700°K. The four

specimens studied were n-type; two were polycrystalline, and two single-crystal.

634. EPSTEIN, A. S., FRITZSCHE, H. and LARK-HOROVITZ, K. **Electrical properties of tellurium at the melting point and in the liquid state.** *Phys. Rev.* **107**: 412–419, 1957.

The electrical resistivity, the Hall coefficient, and the thermoelectric power of spectroscopically pure Te decrease abruptly at the melting point, 445°C. The last two properties are positive up to ~ 575°C, but there reverse their sign and remain negative up to the highest temperature measured, ~950°C. The resistivity of the liquid metal decreases as the temperature increases to a constant value of 3·6 x 10^{-4}Ωcm. at ~650°C. The results show that Te is a p-type semiconductor at low temperatures but is intrinsic at higher temperature, the semiconducting properties being retained in the liquid state. Further increase of temperature brings about a gradual transition to metallic conduction.

635. ERDMANN, J., SCHULTZ, H. and APPEL, J. **The magnetic variation of thermoelectric power of Ge single crystals at low temperatures.** *Z. Naturforsch.* **12A**: 171–174, Feb. 1957.

Results of measurements on pure n-type specimens are briefly reported and discussed. The changes of thermoelectric power as a function of magnetic field strength in the range 0—17 kG are plotted for 22·9, 59·0 and 82·4K.

636. ERDMANN, J. **The change in thermoelectric power with magnetic field in germanium at low temperatures.** *Z. Naturforsch.* **13a**: 650–662, Aug. 1958.

In German.

The change in thermoelectric power with magnetic field for p-germanium with different doping levels is reported. The measurements were performed between 20° and 90°K. The following results were found: (1) The change in thermoelectric power has the same dependence on the magnitude and the orientation of the magnetic field as does the magnetoresistance. (2) The change in thermoelectric power decreases with increasing contribution of ionised impurity scattering mechanism. The measured results are in good qualitative agreement with a theory of Appel, which considers the deviation of the lattice vibrations from thermal equilibrium. The anisotropy of the change in thermoelectric power is discussed on the basis of the theory of Abeles and Meiboom.

637. EVRAETS, J. C. **Thermoelectric material.** U.S. Patent 2,881,236.

Abstracted in: U.S. Patent Office Official Gazette **741(1)**: 224, Apr. 7, 1959.

A thermoelectric element of a thermocouple is composed of an alloy containing 6–25% Mo, 2–10% Cr and the balance iron.

638. FAGEN, E., GOFF, J. and PEARLMAN, N. **Thermal conductivity and thermoelectric power of germanium at low temperatures.** *Phys. Rev.* **94**: 1415, 1954.

Abstract only of paper given at meeting of the American Physical Society, Detroit and Ann Arbor, Mich., March 1954.

"The effect on low-temperature thermal conductivity, k, and thermoelectric power, Q, of semiconductors, due to neutron bombardment, is being investigated.

639. FAUS, H. T. and RIDGLEY, D. E. **Thermoelectric element.** U.S. Patent 2,712,563 (to General Electric), Jly, 1955.

The alloys used are prepared by melting a mixture of In and Te in the desired proportions and casting into suitable forms. The resistivity of the thermocouple elements increases linearly to a maximum of about 1·8 ohms when indium content is 18–24%. While the thermocouple elements of this invention can be used with any suitable negative element having a high negative thermal-emf, preferred negative elements are those containing about 58% Te and 42% Bi.

640. FAUST, J. W., JR. **The etching of $Bi_2Te_xSe_{(3-x)}$.** *In* Westinghouse Research Laboratories, Pittsburgh, Pa., Thermoelectricity Progress Report 12, 5 p., illus., Jan. 1959.

Limited availability.

Dwells briefly on the mechanical Process and discusses chemical and electrolytic etches.

641. FIELDING, P. E. and GUTMAN, F. **Electrical properties of phthalocyanines.** *J. Chem. Phys.* **26**: 411–419, Feb. 1957.

The electrical conductivity of a single crystal of metal-free copper, nickel, and cobalt phthalocyanines were measured over temperature ranges extending from 50 to 390°C. The weighted mean values of the activation energies obtained were 1·71 eV for the metal-free, 1·60 eV for the cobalt, and for the nickel, and 1·64 eV for the copper substituted compounds. A thermoelectric power of +50 μ V/°C was measured for metal-free and for copper phthalcyanine, indicating that the majority of carriers are holes. Since the values of the constant σ_o were found to be in the order of $100\Omega^{-1}$ cm^{-1} it is concluded that their mobilities are rather low.

642. FINLAYSON, D. M. and GREIG, D. **Thermoelectric measurements on natural galena at low temperatures.** *Phys. Soc. Proc.* **73**: 49–53, figs., Jan. 1, 1959.

The thermoelectric power of n-type single crystals of natural galena has been measured down to liquid hydrogen temperatures. The theory developed by Howarth and Sondheimer fits the experimental results fairly well. An electron effective mass ratio in the range 0·11–0·19 was obtained. No evidence of phonon drag effects was observed.

643. FISCHER, GASTON; WHITE, G. K. and WOODS, S. B. **Thermal and electrical resistivity of tellurium at low temperatures.** *Phys. Rev.* **106**: 480–483, May 1, 1957.

The maximum thermal conductivity in the case of a single crystal of 3-mm. diameter is about 10 watts per cm. deg. at 4K.

644. FISCHER, MARGARETE and HILLER, J. E. **The thermoelectric effect of pyrite.** *Neues Jahrb. Mineral Abh.* **89**: 281–301, 1956.

In German. Not examined.

"Measurements were made on 55 samples of various types of origin. Some samples showed considerable variation from one part of a single crystal to another. No relation could be established between the sign or magnitude of the thermoelectric effect and the crystal form or the temperature of formation contrary to Smith. Qualitative spectrographic analyses indicated that Co, Ni, and Cu were highest in samples giving negative effects: As, Sb, and Mn were highest in those giving positive effects. Unit-cell determinations on 17 samples gave 5·412–5·418±0·001 A; one other sample gave a 5·465±0·001 A." *Chem. Abs.* **51**: 2477, 1957.

645. FISCHER, W. A. and LORENZ, G. **Development of an oxide thermocouple.** *Arch. Eisenhuttenw.* **29**: 292–300, 1958.

In German.

The thermal emf of the oxide couple described is up to 100 times greater than those of metallic thermocouples, is reproducible and remains unchanged even after continuous and repeated heating. The emf of 1700°C is quoted as 246 mV.

646. FISCHER, W. A. and LORENZ, GERT. **Elektrische widerstandsund thermokraftmessungen an chrom (III)—Oxyd bei temperaturen bis 1750°. (Measurements of the electrical resistance and thermoelectrical force in chromium (III)—oxide at temperatures up to 1750°).** *Arch. Eisenhuttenw.* **28**: 497–503, Aug. 1957.

In German.

Conductivity of chromium (III) oxide from 900 to 1750°C. Calculation of the transport number of Cr^{3+} ions in chromium (III)—oxide at 1500°C. Effects of additions of metal oxides on electrical properties.

647. FOSTER, A. W. **Thermoelectric property of nickel-chromium alloys.** *Phil. Mag.* **18**: 470, 1934.

The thermoelectric power with respect to copper is determined for various alloys of nickel and chromium.

648. Franklin Institute. Laboratories for Research and Development, Boston, Mass. **Research in thermoelectricity.** Final Report, by C. A. DOMENICALI. n.p., 1955. (AD 64170).

Work on the purification of Sb and Te for investigating the electrical and thermoelectric properties of the Sb–Te system. Studies were made between −195 to 600°C.

649. Franklin Institute Laboratories for Research and Development, Philadelphia, Pa. **Development of thermocouples for use on thermoelectric generators.** Final Report, 30 April 1947—30 September, 1950. 48 p., 1950. (Rept. F-1992-12) (Contract W36-039-sc-33654) (PB 144 088).

The development of Zn-Sb alloys, properties of PbS, and the design and construction of an experimental thermoelectric generator. Thermoelectric properties have been investigated most thoroughly for PbS and the intermetallic compound Zn–Sb.

650. FREDERIKSE, H. P. R. **Compound semiconductors.** *J. Metals.* **10**: 346–350, illus., May 1958.

Thermoelectric power, p. 350.

651. FREDERIKSE, H. P. R. **Thermoelectric power of germanium below room temperature.** *Phys. Rev.* **92**: 248–252, Oct. 15, 1953.

Measurements were made on n-type Ge samples in the range 10–300 K. The temperature dependence at temperatures above 200 K is in good agreement with conventional theory but below this temperature the thermoelectric power rises sharply above the predicted value and reaches a maximum of several millivolts per degree (with Cu) at 15 K. This deviation is due to the disturbance of the phonon equilibrium.

652. FREDERIKSE, H. P. R. and MIELCZAREK, E. V. **Thermoelectric power of indium antimonide.** *Phys. Rev.* **99**: 1789–1890, Sept. 15, 1955.

Measurements of the thermoelectric power of a p-type and an n-type specimen over the temperature range 60–400°K are reported; wide differences are found between the two characteristics.

653. FREDERIKSE, H. P. R. **Thermoelectric power in germanium single crystals.** *Phys. Rev.* **91**: 491, Jly. 15, 1953.

Abstract only.

"Agreement with Q=(k/e) (const-J/T), was obtained above 200°K. Below this temperature, Q rises sharply above the value given by the above formula. A maximum Q of several mv per degree is reached near 15°K and approaches zero as T approaches zero. The above formula is obtained on the assumption that the phonons of the lattice are in equilibrium. This, however, does not hold in insulators and semiconductors where most of the heat flow is carried by phonons. It can be shown that this leads to an extra term for Q proportional to the ratio of phonon to electron mean free paths. The former can be estimated from the thermal conductivity whereas the latter is known from electrical measurements. Using these values the sharp rise of Q below 200°K can be accounted for by the extra term." Entire item quoted.

654. FREDERIKSE, H. P. R. and HOSLER, W. R. **Thermoelectric power of titanium dioxide.** *Am. Phys. Soc. Bull.* **4**: 180, Mar. 30, 1959.

Abstract only.

"Rutile single crystals were reduced to different extent (weight loss 0·01–0·1% or doped with pentavalent ions (Ta, Nb) by diffusion. Both

treatments produce a light to dark colour depending on the concentration of vacancies or foreign ions. The thermoelectric power Q(300–1200°K) resistivity p(4–1200°K) and the Hall coefficient R(~30–600°K) were measured as a function of temperatures in the indicated ranges. The temperature dependence of the reduced and the doped samples is qualitatively the same above 78°K. The Hall mobility depends on the crystallographic direction, but varies little between samples (for T > 200°K). Both the energy band picture and the localised level model were used in analysing the thermoelectric data. From the band picture one obtains an effective mass of the order of 10–80 m_0 in reasonable agreement with previous results. The density of states is in both cases within an order of magnitude of the number of Ti ions. It is suggested that the conduction around room temperature takes place in a very narrow 3d band of Ti." Entire item quoted.

655. FUKUORI, T., TANUMA, S. and TOBISAWA, S. **Electrical properties of antimony-doped tellurium crystals.** *Tohoku Univ. Res. Inst. Sci. Rpt.* **A4**: 283–297, illus., 1952.

Electrical resistivity, Hall effect and thermoelectric power of tellurium crystals alloyed with antimony of quantities between 0·002 and 5 atomic per cent have been measured in the temperature range from liquid air temperature to 300°C, and the data are compared with the properties of pure tellurium crystals with a view to clarifying the change electrical properties accompanying the increase of acceptor impurities.

656. FUKUORI, T., TANUMA, S. and TOBISAWA, S. **Electric resistance, Hall effect, magnetoresistance and Seebeck effect in a pure tellurium film.** *Tohoku Univ. Res. Inst. Sci. Rpts. Ser.* **1A**: 365–373, Dec. 1949.

Measurements were carried out on Te films, deposited by evaporation on glass plates, between −195° and 60°C. The temperature variation of resistance was measured, the temperature coefficient being negative. The Hall coefficient is positive and proportional to the resistance. The thermoelectric power (against Al) is positive with an anomalous change of slope at −100°C. The results are briefly discussed from the standpoint of semiconductor theory.

657. FUKUORI, T., TANUMA, S. and TOBISAWA, S. **On the electromagnetic properties of single crystals of tellurium. I. Electric resistance, Hall effect, magnetoresistance, and thermoelectric power.** *Tohoku Univ. Res. Inst. Sci. Rpt. A.* **1**: 373–386, diags., 1949.

The resistivity, the Hall, the magneto resistance, and the Seebeck effects are investigated with respect to the highly purified single crystals of tellurium over the temperatures ranging from −190 to +300°C. The said crystals are found to be a p-type extrinsic semiconductor at low temperatures, while an intrinsic conduction supersedes it above ice point. The energy gap between the conduction band and the normally filled band are estimated at 0·34 eV. In terms of the electric and the galvanomagnetic data, the concentrations, the mobilities, the effective masses, and the mean free paths of positive holes and electrons are expressed as functions of temperature. The thermo-emf data are also compatible with the above results.

658. FUKUROI, T. and TANUMA, S. **Thermoelectric power of the non-polar semiconductor, that of tellurium crystals, as an example.** *Tohoku Univ. Res. Inst. Sci. Rpts.* **4A**: 353–368, Aug. 1952.

To explain the experimental results on the thermoelectric power of the crystals of pure tellurium and those alloyed with less than 5% antimony, and thermoelectric power of the non-polar composite semiconductor in general has been derived. Numerical calculations carried out for tellurium crystals have shown that the measured characteristics can well be accounted for throughout the temperature range being studied. The quantitative discordance observed at higher temperatures has been explained by a more or less elaborated theory in which a dual-band structure which consists of two overlapped energy bands is assumed for the conduction band, the same band scheme being compatible with other electric properties of tellurium.

659. FULLER, T. S. **Thermoelectric force of certain iron alloys.** *Electrochem. Soc. Trans.* **27**: 241–251, 1915.

Thermocouples having elements of various iron alloys are discussed. Their electromotive forces are listed.

660. FUMERON—RODOT, H. and RODOT, MICHEL. **Some properties of mercury telluride.** *Acad. Sci. Paris. Compt. Rend.* **248**: 937–940, Feb. 16, 1959.

In French.

Specimens of n- and p-type HgTe were prepared. The room temperature Hall mobility of electrons was as high as 22000 $cm^2V^{-1}sec^{-1}$. The mobility ratio was in agreement with the value of 70 given by Lawson, Nielson and Young. Studies of the magnetothermoelectric effect and of the Nernst effect from 77° to 300°K suggest that the mobility is limited by collisions of the electrons with the acoustic phonons.

661. FUSCHILLO, N., BIERLY, J. N. and DONAHOE, F. J. **Transport properties of the pseudo-binary alloy system $Bi_2Te_{3-y}Se_y$.** *In* Advances in Semi-Conductor Science. Proceedings of the Third International Conference of Semiconductors held at the University of Rochester Aug. 18–22, 1958, p. 430–433, New York, Pergamon Press, 1959.

The alloy system $Bi_2Te_{3-y}Se_y$ has been the subject of a number of investigations in recent years because of the possible application of these alloys in thermoelectric devices. In this paper is presented a systematic study of the temperature variation of the electrical conductivity, σ, and the

Seebeck coefficient, S, and the room temperature thermal conductivity, K, as Se is substituted for Te in the molecular formula $Bi_2Te_{3-y}Se_y$ until Bi_2Te_3 is transformed into Bi_2Se_3.

662. FUSCHILLO, N. **Critical study of asymmetrical temperature gradient thermoelectric effect in copper and platinum.** *Phys. Soc. Proc.* **65**: 896–904, Nov. 1, 1952.

Experiments in producing pronounced asymmetrical temperature-gradients in metallic wires without mechanically straining; measurement of electromotive forces developed; relation to improved method for testing and selecting wire for thermoelectric thermometers.

Includes bibliography.

663. FUSCHILLO, N. **Thermoelectric effects due to stationary and moving asymmetrical temperature gradients in mercury.** *Phys. Soc. Proc.* **66**: 649–653, Aug. 1, 1953.

Experimental data are compared with earlier work on Cu and Pt.

664. GAINES, G. B. and SIMS, C. T. **Electrical resistivity and thermoelectric potential of rhenium metal.** *Am. Soc. Test. Mat. Proc.* **57**: 759–768, 1957.

Thermoelectric potentials (E in mV) of junctions between Rh and Mo, W, and Ta, respectively, were measured from 870 to 2490°C. Rh/Ta junctions are unstable with time at a particular temperature and are of no value as thermocouples.

665. GALGINAITIS, S. V. **Physical properties of thermoelectric materials.** *Refrig. Eng.* **66**: 46–48, Jly. 1958.

Following the development of the potentialities of the Peltier effect from the engineering aspect, the subject is approached from the angle of materials which may be selected for the purpose.

666. GALKIN, G., DOLGIKH, G. and YURKOV, V. **Electric properties of Sb_2S_3 and of Bi_2S_3.** *Zhurn. Tekh. Fiz.* **22**: 1533–1539, 1952.

In Russian.

The experiments were to study the variation of electric conductivity and of thermo-emf as functions of temperature, in sulfides of Bi and Sb, carrying various amounts of S in excess of the stoichiometric formulaes. The technique for the production of samples is described in detail. Measurements were by the ordinary compensation method. For Sb_2S_3 the curves of σ and α as functions of temperature were established in the interval 150–300° and in some cases 250–450°. The curves show that σ and α decrease when the excess of S is removed by heating in a stream of H. For Bi_2S_3 it was discovered that the thermo-emf of the samples once heated corresponded at room temperature to predominantly electron-hole conductivity. The curves of thermoemf as a function of temperature showed that the emf of the couple Ni-Bi_2S_3 changes sign in the region 150–200°. Electron-hole conductivity at lower temperature passed to electron conductivity at higher temperature. The curves of σ and α as functions of temperature are analogous. After the samples are heated in S vapour the electron-hole component of the conductivity disappears.

667. GEBALLE, T. H. **Group IV semiconductors.** *In* Hannay, N. B., ed. Semiconductors, p. 313–388, N.Y. Reinhold, 1959. (*Am. Chem. Soc. Monograph Series* 140).

Includes information on thermal transport problems, thermal conductivity, thermoelectricity of silicon, germanium, and silicon carbide.

668. GEBALLE, T. H. and HULL, G. W. **Isotopic and other types of thermal resistance in germanium.** *Phys. Rev.* **110**: 773–775, 1958.

Letter. Electric conductivity and Hall, thermoelectric, and Nernst effects were measured on a crystal of enriched Ge^{74}. The effect of the presence of isotopes on the thermal conduction and other properties is discussed.

669. GEBALLE, T. H. and HULL, G. W. **Seebeck effeect in germanium.** *Phys. Rev.* **94**: 1134–1140, June 1, 1954.

An apparatus for making measurements of the Seebeck effect between 20 K and 375 K is described. Experimental curves of the Seebeck effect are given for a series of germanium crystals in which various concentrations of acceptor and donor atoms have been incorporated. The Seebeck data are compared with Hall data obtained concurrently. Above 250 K the two effects can be correlated by means of existing theory. Below 250 K a marked discrepancy occurs between existing theory and experiment. The temperature dependence of this discrepancy and its dependence upon concentration of added atoms are given. The results are consistent with a new theory proposed by C. Herring which considers an interaction between the phonon and electron systems. A dependence of Seebeck voltage upon sample dimension which is predicted by Herring's theory has been found in the temperature region below 50 K. A value $(0{\cdot}75 \pm 0{\cdot}2)$ m has been determined for the mass parameter of both holes and electrons which enters into the "density of states" equation.

670. GEBALLE, T. H. and HULL, G. W. **Seebeck effect in silicon.** *Phys. Rev.* **98**: 940–947, May 15, 1955.

The silicon effect has been measured from liquid hydrogen temperatures into the intrinsic range for a series of single-crystal silicon samples in which varying concentrations of donor and acceptor atoms have been incorporated. Large values of Seebeck voltage believed to be caused by the type of phonon-electron coupling previously postulated as occurring in germanium have been found. This effect is found to be dependent upon charge carrier concentration, and upon sample dimension below 100°K. A low-temperature reversal of the sign of the Seebeck voltage is observed for large carrier concentrations. It is understandable in terms of impurity band conduction. The behaviour above room temperature

into the intrinsic range is found to be consistent with electrical conductivity data.

671. GEBALLE, T. H. **Thermoelectricity and conduction in InSb.** *Am. Phys. Soc. Bull.* **2**: 56, 1957.

Abstract only of paper presented at Annual Meeting of American Physical Society, New York, January 30–February 2, 1957.

Measurements of the thermoelectric power, Q, and the thermal conductivity K for p-type InSb from liquid helium to intrinsic temperatures show the following behaviour: For 2×10^{15} excess acceptors per cm^3 a large Q_p, the phonon drag contribution to Q, is observed as reported by Frederikse and Mielczarek. Q_p equals 4800 μv per degree at 30°K, and varies as $T^{-2\cdot4}$ up to 70°K. This temperature dependence, the boundary scattering effect, and a saturation effect observed in less pure material are understandable in terms of Herring's theory.

672. GEIKHMAN, D. S., ROMANKEVICH, V. N. and SIDYAKIN, V. G. **The electrical properties of polycrystalline selenium with halogen impurities (Br_2, Cl_2, I_2).** *Soviet Phys. Solid State* **1**: 196–202, Feb. 1959.

Trans. of Russian article.

The present study investigates the effects of bromine (0·25 to 4% Br), of chlorine (0·001 to 4% Cl), and of iodine (0·001 to 4% I) on the electrical and thermoelectric properties of polycrystalline selenium.

673. GEIKHMAN, D. S., ROBANKEVICH, V. N. and SIDYAKIN, V. G. **The electrical properties of polycrystalline selenium with halogen impurities Br_2, Cl_2, I_2.** *Soviet Phys. Solid State.* **1**: 196–202, Feb. 1959.

The present study investigates the effects of Br (0·25 to 4o/o Br), Cl (0·001 to 4o/o Cl), and I (0·001 to 4o/o I) on the electrical and thermoelectric properties of polycrystalline Se.

Results indicate the thermal emf coefficient a is smaller for halogen-doped specimens than for pure Se.

English translation of article in *Fiz. Tverdogo Tela.* 1: 218–226, Feb. 1959.

674. GEL'D, P. V. **Thermal and thermoelectric properties of alloys of silicon with transition metals.** *Sov. Phys. Tech. Phys.* **2**: 95–99, Jan. 1957.

Translation of Russian article in *Zhurn. Tekh. Fiz.* **27**: 113–118, 1957.

Test results for alloys of silicon and iron, chromium, and manganese. Thermoelectric force thermal conductivity, coefficient of expansion, specific heats, and electrical conductivity are all determined.

675. General Dynamics Corp., General Atomic Div., San Diego, Calif. **High temperature broad band semiconductors.** by S. W. KURNICK. Monthly Progress Report for September 1959. 6 p., illus., Oct. 12, 1959. (Contract Nobs 77144) (AD 228 492)

Efforts are being made to investigate the thermoelectric conductive and galvanomagnetic properties of high temperature, broad-band semiconductors. The study is based, first, on the preparation of Ce-S semiconductors in which nonstiochiometry is pronounced. Similarly, a second system under investigation is that of the solid-state solutions of MgO-CoO-MgO-FeO and MgO-NiO.

676. General Electric Co. Schenectady, N.Y. **Thermoelectric stability of thermocouple materials at elevated temperatures,** by J. M. BERRY and D. L. MARTIN. 30 p., Mar. 1955. (Rpt. 55-RL-1234).

A study of the thermoelectric stability of ten metallic materials was made. In the experimental technique used, the materials were aged isothermally at 780°C, and each material was individually evaluated by comparison with platinum at the steam and zinc melting temperature reference points. The results are believed to be more suitable for the evaluation of thermoelectric stability than are results obtained by testing materials under gradient conditions as thermocouples. In addition, the isothermal results can be used to estimate the performance of thermocouples. It is also concluded that a stabilisation treatment prior to use will improve the stability of some base metal thermocouples. The effects of ageing in air and in a vacuum were studied. Scatter in the data obtained from vacuum-aged specimens suggests that optimistic assumptions about the efficacy of "protective" atmospheres may be unjustified. Very pure nickel and silver are quite stable in air at 780°C. This combination makes a thermocouple which, even after long periods of use, is relatively insensitive to changes in temperature distribution.

677. General Mills, Mechanical Division, Minneapolis, Minn. **Progress report on investigations of bismuth tellurium sulfur compounds.** by H. H. SOONPAA, 21 p., Apr. 7, 1960. (Tech. Rept. 1, Rept. 1940) (Contract Nonr-1589(14)).

This report covers the compound of the composition $Bi_2(Te, S)_3$ with the Te, S ratio ranging from 100 : 0 to 50 : 50.

678. GEORGE, W. R., SHARPLES, R. and THOMPSON, J. E. **The Sintering of bismuth telluride.** *Phys. Soc. Proc.* **74**: 768–769, Dec. 1, 1959.

The use of sintered material was considered to overcome the difficulty, for commercial application such as refrigeration, of fragile zone refined material. p-type zone refined bismuth telluride was made from bismuth and tellurium (purity 1 in 10^6), with iodine doping, by melting the stoichiometric proportions in a closed evacuated tube and subsequent zone refining. The material was crushed to 100-mesh size and the resulting powder compacted at various temperatures. The samples were sintered at temperatures up to the melting point.

This note records variation of the thermoelectric power of bismuth telluride with sintering temperature.

679. GLASCOCK, H. H. and HENSLEY, E. B. **Thermoelectric effect and electrical conductivity of calcium oxide.** *Am. Phys. Soc. Bull.* **2**: 271, June 20, 1957.

Abstract.

"The qualitative similarity of measurements of the electrical conductivity and thermoelectric effect of sprayed aggregates of CaO to measurements made on (BaSr)O by Young suggest that CaO is also a pore conductor.

Plots of the thermoelectric power vs the reciprocal temperature exhibited a maximum in the neighbourhood of 1100°K and dropped sharply in the vicinity of the break in the conductivity curve. The shape of the thermoelectric curve was very similar to the case of (BaSr)O."

680. GLICKSMAN, M. **The magnetoresistance of electrons in InP and GaAs.** *Phys. & Chem. Solids* **8**: 511–515, figs., 1959.

The band structure of n-type InP was investigated by galvanomagnetic, optical and thermoelectric power measurements.

681. GOFF, J. F. and PEARLMAN, N. **Transport properties of compensated degenerate germanium. I. Electrical resistivity and thermoelectric power.** *Am. Phys. Soc. Bull.* **4**: 410, Nov. 27, 1959.

Abstract of paper.

The effect of gallium compensation of antimony doped germanium single crystals on the electrical resistivity p and the thermoelectric power Q has been observed between 1·2 and 80°K.

682. GOFF, J. F. and PEARLMAN, N. **The transport properties of semiconductors at low temperatures.** *In* Purdue University. Dept. of Physics. Semiconductor Research. Twelfth Quarterly Report, May to July 31, 1959, p. 8–11, Lafayette, Ind., Purdue University, 1959.

The thermal conductivity K, thermoelectric power Q, and the electrical resistivity p are being measured for a single crystal germanium sample with an estimated total impurity concentration N_I 2·0 × 10^{18} cm^{-3} and an exhaustion electron concentration n_{ex} 25·3 × 10^{17} cm^{-3}.

683. GOFF, J. F. and PEARLMAN, N **The transport properties of semiconductors at low temperatures.** *In* Purdue University. Dept. of Physics. Semiconductor Research. Eleventh Quarterly Report, February 1 to April 30, 1959, p. 812–, Lafayette, Ind., Purdue Research Foundation and U.S. Signal Corps., 1959. (PRF Rept. 1258) (Contract DA36-039-sc-71131).

In addition to having continued the investigation of the behaviour of n-type, heavily compensated germanium, the thermal conductivity, thermoelectric power, and the electrical resistivity of a p-type indium antimonide sample have been measured. These samples are discussed separately.

684. GOFF, J. F. and PEARLMAN, N. **Transport properties of germanium at low temperatures.** *In* Purdue University, Dept. of Physics. Semiconductor Research. Thirteenth Quarterly Report, August 1 to October 31, 1959, p. 13–15, figs., Lafayette, Ind., 1959. Purdue University (Contract DA36-039-sc-71131).

Extensions to about 150°K of data on thermal conductivity K, thermoelectric power Q and electrical resistivity p for a single germanium sample.

685. GOLAND, A. N. and EWALD, A. W. **Thermoelectric power of gray tin.** *Phys. Rev.* **104**: 948–953, Nov. 15, 1956.

The measured power of p-type samples is analysed into electronic and phonon contributions with Hall and electrical conductivity data.

686. GOLAND, A. N. and EWALD, A. W. **Thermoelectric power in grey tin filaments.** *Semiconductor Abs.* **4**: 466, 1956.

Abstract only of paper given at American Physical Society meeting, Washington, D.C., April 26–28, 1956.

"Thermoelectric power measurements have been carried out on grey tin filaments in the temperature range from 77 to 270°K for pure samples, and for n-type and p-type samples with varying impurity concentrations. Pure samples are always n-type, and exhibit a maximum of approximately −100 microvolts/°K in the neighbourhood of 100°K. Other n-type samples have a maximum of about −160 microvolts/°K at somewhat higher temperature, and this maximum shifts to higher temperature as the impurity concentration is increased. The p-type samples also exhibit a maximum of the order of 140–160 microvolts/°K which occurs in the range 90–100°K. All p-samples become n-type as the temperature rises, and the crossover point shifts to higher temperature as impurity concentration increases. Preliminary analysis indicates that the phonon effect may be much more important in p-type than in n-type material." Entire item quoted.

687. GOL'BERG, A. I., LIPATOVA, V. A. and GEL'D, P. V. **Electrical properties of iron-silicon alloys.** *Ural. Politekh. Inst. im S.M. Kirova, Sbornik. Trudy.* **72**: 252–254, 1957.

In Russian.

"Alloys were prepared containing between 47 and 59% Si in Fe. The samples were annealed at 800° for 10 to 12 hours and slow-cooled, or 1000° and water-quenched. Electrical resistivity, Hall coefficient, and thermoelectric power were measured at room temperature. The results were presented graphically and all of the measured parameters show a large discontinuity at 50%. Both the Hall coefficient and thermoelectric power were positive at this composition and passed through zero at approximately 47 and 53%.

688. GOLDSMID, H. J. **Heat conduction in bismuth telluride.** *Phys. Soc. Proc.* **72**: 17–26, Jly. 1958.

The Lorenz number of the semiconductor Bi_2Te_3 has been evaluated, for the range of partial degeneracy, from data provided by the measure-

ments of electrical conductivity and thermoelectric power. The calculated electronic component of the thermal conductivity, for p-type material, has been found to agree with the experimental results, assuming the lattice thermal conductivity to be independent of the electrical conductivity.

689. GOLDSMID, H. J. **The electrical conductivity and thermoelectric power of bismuth telluride.** *Phys. Soc. Proc.* **71**: 633–646, Apr. 1958.

The electrical conductivity and thermoelectric power of the semiconductor Bi_2Te_3 have been measured between 150 K and 300 K. Both n-type and p-type samples with a wide range of carrier concentration have been included. Most samples have shown extrinsic conduction and have been partially degenerate over at least part of the temperature range, so it has been necessary to use Fermi Dirac statistics in interpreting the results. A few samples have exhibited mixed and intrinsic conduction at the higher temperatures. It has been possible to determine the variation of carrier mobility with temperature and to estimate the energy dependence of the relaxation time, as well as a number of the semiconductor parameters.

Also in *Semiconductor Electronics*, **2**: 2000, Jly, 1958; in *Metals Rev.* **31**: 356-P, Aug. 1958; *Electronic & Radio Engr.* **35**: 2473, Aug. 1958, *Nuclear Abs.* **12**: 9238, Jly. 31, 1958 and in *Brit. Sci. Instr. Res. Assoc. Bull.* **13**: 163, June, 1958.

691. GOLDSMID, H. J., JENNS, C. C. and WRIGHT, D. A. **The thermoelectric power of a semiconducting diamond.** *Phys. Soc. Proc.* **73**: 393–398, Mar. 1, 1959.

The thermoelectric power of a p-type semiconducting diamond has been measured in the temperature range 220–700°K. After subtracting an electronic component, estimated from the previous Hall effect measurements on the sample, it has been possible to determine the phonon-drag component of the thermoelectric power. This component has been found to vary with temperature approximately as $T^{-3\cdot6}$, with a value of about 2·5 mV deg^{-1} at room temperature. The magnitude of the effect is of the order to be expected from the known behaviour of germanium and silicon.

691. GOLDSMID, H. J., SHEARD, A. R., and WRIGHT, D. A. **The performance of bismuth telluride thermojunctions.** *Brit. J. Appl. Phys.* **9**: 365–370, figs., Sept. 1958.

The thermoelectric properties of n-type and p-type bismuth telluride between 150 and 300 K have been measured and the figure of merit for thermoelectric applications has been calculated. This figure of merit has been shown to be highest for material with an electrical conductivity of about $1000\Omega^{-1}$ cm^{-1} with current flow parallel to the cleavage planes. Its value at 290 K corresponds to a maximum cooling by means of the Peltier effect of about 65°C, and an efficiency of thermoelectric generation of 1% for a 25°C. temperature difference.

692. GOLDSMID, H. J. **On the thermal and electrical conductivity of semiconductors.** *Phys. Soc Proc.* **67B**: 360–363, Apr. 1954.

The ratio of the carrier mobility to thermal condition is shown to vary rapidly and smoothly with mean atomic weight.

693. GOLDSMID, H. J. **The thermal conductivity of bismuth telluride.** *Phys. Soc. Proc.* **69B**: 203–209, Feb. 1956.

Measurements were made in the temperature range 150–300°K. It has been found that the electronic contribution to the conduction of heat is considerably greater for specimens in which the charge carriers are intrinsically excited than for those in which most of the carriers arise from impurity concentration. This can be explained by the proposed theory which takes into account the transfer of ionisation energy down a temperature gradient.

694. GONDO, Y. and FUNATOGAWA, Z. **On the magneto-thermoelectric power of iron crystal at low temperatures.** *Phys. Soc. Japan J.* **7**: 589–592, Nov/Dec. 1952.

The magneto-thermoelectric power of iron single crystal was measured in a temperature region between room temperature and −195°C and the anisotropic constants $(E_m)_{100}$ and $(E_m)_{111}$, respectively, were calculated, at various temperatures reported in an earlier work; both the constants were found to have maximum values near room temperature and decrease gradually with decreasing temperature, perhaps tending to zero at 0°K.

695. GORDYAKOVA, G. N., KOKOSH, G. V. and SINANI, S. S. **An investigation of thermoelectrical properties of Bi_2Te_3-Bi_2Se_3 solid solutions.** *Zhurn. Tekh. Fiz.* **28**: 3–17, Jan. 1958.

In Russian.

Translation in *Soviet Phys. Tech. Phys.* **3**: 1–14, Jan. 1958. Translation no. R-4017 available at Special Libraries Assn. Translation Centre, Crerar Library, Chicago, Ill. Also in Infosearch Tech. Lit. Info. Serv. Russian Lit. Survey SEM-5-58, p. 1·1–1·14, Bull. 34: B491, Jly. 15, 1958.

The major part of this investigation constituted a study of the effect of additives on the solid soln. of Bi_2Te_3 and Bi_2Se_3. The additives used were elements and compounds.

It was established that acceptor effects were exhibited by elements of the 2nd, 3rd, 4th, 5th and 8th groups of the periodic table, and donor effects were characteristic of halogens, Cu, Ag, Te, and Se. The p-type alloys possessed low values of activity and $\alpha^2\sigma$ where α=thermo-emf in microv./degree and σ=electrocond. in ohm^{-1}. cm^{-1}. Alloys of n-type, however, were obtained with sufficiently high values for practical use. Better thermoelec. properties were obtained with halide additives of the 1st group than with elemental Cu. In samples of optimum compn. the value of $Z=\alpha^2\sigma/x$, where x=thermo-cond. was as high as $2\cdot5\times10^{-3}$/degree.

696. GORDYAKOVA, G. N. and SINANI, S. S. **Thermoelectric properties of bismuth telluride with alloying additives.** *Soviet Phys. Tech. Phys.* **3**: 908–911, 1958.

Translation of *Zhurn. Tekh. Fiz.* **28**: 977–980, 1958.

697. GORDYAKOVA, G. N. and SINANI, S. S. **Thermoelektricheski svoistva tellurida vismuta s legiruyuschimi dobavkamii. (Thermoelectric properties of bismuth telluride with alloying admixtures)** *Zhurn. Tekh. Fiz.* **28**: 977–980, May 1958.

In Russian.

Translation in Infosearch Tech. Lit. Info. Serv. Russian Lit. Survey SEM-5-58, p. 2·1–2·4.

The temperature dependence of electrical conductivity and thermal emf of Bi_2Te_3 doped with various amounts of I, Pb, Cu and CuBr was studied. p-type specimens with good thermoelectric properties and values of $\alpha^2\sigma$ of up to $32\mu V^2/deg \times ohm \times cm$ were obtained by adding Pb. n-type specimens were obtained with I and CuBr. Values of $\alpha^2\sigma$ of 20 and more may be obtained at 300–350°C.

698. GORTER, C. J., VAN DEN BERG, G. J. and DE NOBEL, J. **Remarks on the anomalous behaviour of alloys containing traces of manganese or similar elements.** *Can. J. Phys.* **34** (Suppl. **12A**): 1281–1284, Dec. 1956.

While rapid decrease of electric resistance sometimes occurring at very low temperatures apparently must be attributed to some kind of antiferromagnetic alignment, the resistance minimum, as well as anomalies in thermoelectricity and the Hall effect, might be due to gaps at crystalline boundaries.

699. GRANT, F. A. **Properties of rutile (titanium dioxide).** *Revs. Mod. Phys.* **31**: 646–647, Jly. 1959.

Literature on physical properties of rutile is examined critically.

Thermopower is discussed, p. 653 and 659.

700. GRATTIDGE, WALTER, and JOHN, HAROLD. **The electronic properties of barium sulfide.** *J. Appl. Phys.* **23**: 1145–1151, Oct. 1952.

Includes chemical preparation, thermionic emission, electrical conductivity, thermoelectric power, and vapour pressure.

701. Great Britain. Atomic Energy Research Establishment, Harwell. **Preliminary measurements on the thermoelectric power of plutonium metals.** by J. A. LEE and R. O. A. HALL. 9 p., Jan. 1959. (Rept. M/R 2800).

The thermal emf of a plutonium-platinum thermocouple has been measured between 20°C. and 630° C, and the absolute thermoelectric power of plutonium in its six allotropic modifications calculated over their stable temperature range. The implications of the results in relation to the form of the density of states/energy curve at the Fermi surface are discussed.

702. Great Britain. Atomic Energy Research Establishment, Harwell. **The electrical gas resistivity and thermoelectric power of neptunium metal in the range 300-900°K,** by J. A. LEE *et al.* 12 p., 1959. (AERE-R-2893).

The electrical resistance of a sample of neptunium metal has been measured between 300 and 900°K. and the resistivity of neptunium in its three allotropic modifications calculated. A measurement of the thermal emf of a neptunium-platinum thermocouple has been made within the stable temperature range of each allotrope, and the corresponding absolute thermoelectric powers calculated. The results are discussed briefly.

703. GREENWOOD, N. N. and ANDERSON, J. S. **Conductivity and thermoelectric effect in cuprous oxide.** *Nature* **164**: 346–347, Aug. 27, 1949.

The thermoelectric power of cuprous oxide was found to be independent of temperature over the range in which the material displayed positive hole conduction. From conductivity measurements the activation energies at low and high temperatures were determined as about 0·26 eV and 1 eV respectively. At temperatures above 350°C the thermoelectric power decreases, probably due to the onset of intrinsic conduction, but does not change sign. Care was taken to use specimens in well-defined states of chemical equilibrium. It is concluded that the thermoelectric properties of impurity semiconductors whose composition is nearly stoichiometric are not adequately described by present theories.

704. GREINER, E. S. and ELLIS, W. C. **Thermal and electrical properties of ductile titanium.** *Metals Tech.* **15**: *Tech. Pub.* 2466, p. 1–9, Sept. 1948.

Thermoelectric properties are determined; and the thermoelectric force of specimens of titanium, from two lots, against platinum for temperatures between 200 and 1000°C are shown in figure 4.

705. GUBANOV, A. I. **Elektroprovodnost, teploprovodnost termoeds, postoiannaia kholla I postoiannaia nernsta dlia amorfnykh tel s electronnoi provodimost'iu. (Thermo emf, electroconductivity, Hall constant, and Nernst constant for amorphous substances with electronic conductivity.)** *Zhurn. Tekh. Fiz.* **27**: 3–11, Jan. 1957.

In Russian.

Translation in *Soviet Phys. Tech. Phys.* **2**: 1–8, Jan. 1957.

A study of the effects of temperature on various kinetic coefficients of amorphous conductive substances and a calculation of the specific dispersion of the electrons; connected with the absence of a remote arrangement.

706. GUSEVA, L. N. and OVECHKIN, B. I. **Thermoelectric properties of chromium silicide.** *Akad. Nauk. SSSR. Dok.* **112**: 73–75, 1957.

Study of electrical and thermoelectrical properties of chromium silicides reveals existence of two groups: Cr_3Si, Cr_5Si_3 and CrSi having con-

ductivities of metals and $CrSi_2$ which is a semiconductor with an activation energy of 1·3.

707. GUSEVA, L. N. and OVECHKII, B. I. **Thermoelectric properties of chromium silicides.** *Akad. Nauk. SSSR. Dok.* **112**: 681–683, 1957.

In Russian.

Measurement was carried out on the thermoelectric properties of Cr silicides. The electrical conductivity of alloys in the range 0–40% Cr rises slightly with increasing Cr content, for the compound $CrSi_2$ it is ~ 150 ohm^{-1} cm^{-1}. On further increase in the Cr content of the alloys the conductivity rises sharply and at 65% Cr reaches its maximum value. The thermoelectric powers in the alloys also change with composition. At low Cr, concentrations the thermoelectric powers fall to zero, then change in sign, and near the composition $CrSi_2$ reach the maximum positive value, then falling again. The compounds Cr_3Si, Cr_5Si_3 and CrSi have a conductivity of a metallic nature, the compound $CrSi_2$ is a semiconductor with an activation energy ~ 1·3 eV. X-ray and metalographic investigations confirmed the existence of the compound Cr_5Si_3; Cr_2Si and Cr_3Si_2 mentioned earlier was not found.

708. HAASE, G. and SCHNEIDER, G. **Studies on thermoelements from the rhenium-iridium system.** *Z. Physik* **144**: 256–262, 1956.

Atomic Energy Commission Translation 3835.

709. HALL, W. J., RODER, H. M. and POWELL, R. L. **Thermal and electrical conductivity of aluminium and aluminium alloys.** *In* International Conference on Low Temperature Physics and Chemistry. Proceedings, 5th, 1957, p. 389–391, figs., Madison, University of Wisconsin, 1958.

Measurements of the thermal and electric conductivity and thermal emf of eight aluminiums in the temperature range 4 to 120°K.

710. HANLEIN, W., GUNTHER, K. G. **Thin films of bismuth telluride.** *Naturw.* **46**: 319, 1959.

"Thin films of the semiconductor Bi_2Te_3 were formed by simultaneous evaporation of Bi and Te from separate crucibles at different temp. T_1 and T_2. By control of these temp. and that of the deposition site (T_3), the required alloy compn. can be deposited. With Bi at 750°C. T_3 was established at 450°C. Variations from this condition gave a two-phase deposit. The nature of the film was established by X-ray diffraction and elect. measurements. The n-type layer with charge carrier concn. of 2×10^{19}/c.c. agrees in mobility (~200 cm^2/V. sec) and in thermoelect. power (200μV)°C, reference Cu) very closely with the same properties in bulk material." *Metall. Abs.* **27**: 430, Mar. 1960.

711. HARADA, Z. and HARIYA, Y. **The thermoelectric potential of pyrite from the Tsuchiya Ishizaki mine, Hokkaido, Japan.** *Minerol. J. (Japan).* **1**: 97–10º, 1954.

In English.

A wide variation of the thermoelectric potentials, ranging from 19·82 mv to −12.32 mv., is observed on pyrite from the Tsuchiya Ishizaki Mine. Specimens associated with Cu ores show negative potential. X-ray studies show that the potentials of nearly perfect crystals have positive low or negative values, while those of crystals with structural irregularities have positive high values. There is no decisive effect of chemical composition upon variation of thermoelectric properties. though the atomic ratio of S to Fe varies from 2·01 to 1·95. It is concluded that structural irregularities may have more influence upon the thermoelectric properties of pyrite than any other factors.

712. HARMAN, T. C, MILLER, S. E. and GOERING, H. L. **Preparation and electrical properties of Bi_2Te_3.** *In* Trabajos Reunion Intern. Reactividao Solidos 3, Madrid, 1956, p. 377–384, 1957.

Not examined. (In English).

"Ingots made from stoichiometric amounts of Bi and Te are p-type. Bi_2Te_3 has a small energy gap, a mobility similar to Pb compounds, and doubly doped surfaces have low thermoelectric power and low intrinsic resistivity." Navy Material Lab. Lib. Info. Bull. Suppl. 9 "Thermoelectricity."

713. HARMAN, T. C., MILLER, S. E. and GOERING, H. L. **Preparation and electrical properties of Bi_2Te_3** *Semiconductor Abs.* **3**: 713, 1955.

Abstract only of paper given at meeting of the American Physical Society, Chicago, Ill., Nov. 25–26,1955.

"Bi_2Te_3 was prepared by a number of techniques from zone-melted Bi, and Te which was purified by multiple distillation. For thermoelectric device applications, it was found that the best technique for preparing both n-type and p-type Bi_2Te_3 is quenching the compound from above its melting point and annealing for long periods of time near its melting point. For the preparation of single crystals for fundamental studies, the best technique was found to be zone melting in a tellurium atmosphere. Bi_2Te_3 dissociates to some extent at the melting point. The elements have segregation coefficients near unity. Iodine and excess Te are n-type impurities in Bi_2Te_3 while Pb and excess Bi are p-type impurities. The resistivity and thermoelectric power were measured as functions of temperature from 200°K to 700°K for n-type and p-type specimens with varying impurity concentrations. A p-type specimen had a thermoelectric power of -180×10^{-6}v/°C at 300°K. The intrinsic resistivity slope indicates a small energy gap." Entire item quoted.

714. HARMAN, T. C., PARIS B., MILLER, S. E. and GOERING, H. L. **Preparation and some physical properties of Bi_2Te_3, Sb_2Te_3, and As_2Te_3.** *Phys. & Chem. Solids.* **2**: 181–190, figs., 1957.

Gives the preparation of the intermetallic compounds Bi_2Te_3, Sb_2Te_3 and As_2Te_3 from purified elements by several techniques and their advantages and disadvantages. Electrical and thermal properties are presented as functions of temperature and impurity concentration. The variation of

carrier mobility with temperature is approximately $T^{-5/2}$ for As_2Te_3 and Bi_2Te_3. An anomalous variation of Hall coefficient with temperatures is observed. The thermal conductivities of the three compounds are similar. It is suggested that the compounds are necessarily heavily doped semiconductors because Group-V atoms appear on tellurium lattice sites and tellurium atoms appear on Group-V atom lattice sites.

715. HARMAN, T. C., LOGAN, M. J., PARIS, B. and LOUGHER, E. H. **Preparation and thermoelectric properties of Bi_2Te_3 and all alloys with Bi_2Se_3.** Programme of the Fall Meeting of the Electrochemical Society, Sept. 1958.

Abstract only.

"Details on the preparation of Bi_2Te_3 and alloys of the compound with Bi_2Se_3 as carried out by a modified Bridgman technique were presented. Resistivity, thermoelectric power, and thermal conductivity were measured as a function of temperature for various specimens. The data show that the lattice thermal conductivity of Bi_2Te_3 is reduced substantially by introducing the electrically neutral impurity atoms by means of alloying. The other thermoelectric properties are changed only slightly. Effects of special preparation procedures and of specimen fabrication were also discussed."

716. HASHIMOTO, K. and HIRAKAWA, K. **Electrical properties of stannous telluride SnTe.** *Phys. Soc. Japan J.* **11**: 716–717, June 1956.

The electrical resistivity, Hall coefficient and thermoelectric power $d\theta/dT$, of SnTe, have been measured between 100°K and 1000°K. Data are summarised by table and graph. The temperature coefficients of electrical resistivity and Hall coefficient are positive for all samples over the whole temperature range. The change of sign of $d\theta/dT$ is found at about 250°C. The theoretical implications of the data are under consideration.

717. HASHIMOTO, KIMIO. **Electrical properties of bismuth selenide, Bi_2Se_3. II. Thermoelectric power and thermal conductivity.** *Kyushu Univ. Mem. Fac. Sci. Ser. B.* **2**: 187–193, 1958.

The thermoelectric power and its relationship to the Hall effect and electrical conductivity were studied. The thermal conductivity of Bi_2Se_3 was also investigated.

718. HAUFFE, KARL and FLINDT, H. G. **Ueber die elektrische leitfaehigkeit und thermokraft von nickelsulfid. (The electrical conductivity and thermoelectric force of nickel sulphide).** *Z. Phys. Chem.* **200**: 199–209, illus., 1952.

In German.

The conductivity σ of NiS and NiS+Ag_2S was measured as a function of the sulfur vapour pressure P_{S2} at 700°C and as a function of the temperature. In the NiS phase σ is independent of P_{S2}, and the temperature coefficient of σ is negative down to liquid air temperatures. For pure Nis $\sigma = 4800^{-1}$ ohm cm^{-1} at 700°C. Addition of Ag_2S decreases σ slightly. At vapour pressures > 100 mm Hg σ decreases continuously with time, probably owing to transition to the NiS_2 phase. The thermoelectric power of Pt/NiS/Pt is about −0·0065 mV/deg. at 700°C, independently of P_{S2}, and that of Pt/NiS_2/Pt is about +0·005 mv/deg. The results are regarded as suggesting that NiS is predominately an intrinsic semiconductor in which the free electrons are degenerate at high temperature.

719. HAYASE, KITARO, HARADA, TANEOMI and OTSUKA, RYOHEI. **The wettability of FeS_2 minerals** *Mining Inst. Japan. J.* **72**: 7–10, 1956.

The wettability to water was measured of FeS_2 minerals (pyrite, marcasite, and melnikovite) from various localities by the Mitsui and Sasakis method. Wettability of pyrite widely differs from specimen to specimen. Melnikovite is not wet, probably owing to rapid surface oxidation. The contact angles were also measured but the values were poorly reproducible. The thermoelectromotive force ranged from 1·53 to 32·36 mv. for pyrite (some were positive and others negative), whereas for marcasite this was always negative. There was a correlation between the wettability and the thermoelectromotive force.

720. HEIKES, R. R. and JOHNSTON, W. D. **Mechanism of conduction in lithium substituted transition metal oxides.** *J. Chem. Phys.* **26**: 583–587, Mar. 1957.

Work done on $Li_xMn_{1-x}O$ compounds demonstrates that the Verweg model is not accurate. Resistance lowers after antiferromagnetic Curie point.

721. HENKELS, H. W. and MACZUK, J. **Electrical properties of liquid selenium. I.** *J. Appl. Phys.* **24**: 1056–1060, Aug. 1953.

Thermoelectric power of liquid Se was measured from 250 to 500°C. Values of activation energies calculated from temperature dependences of thermoelectric powers and resistivities agree.

722. HENKELS, H. W. and MACZUK, J. **Electrical properties of selenium; III. microcrystalline selenium metal doped.** *J. Appl. Phys.* **25**: 1–11, Jan. 1954.

The thermoelectric powers and d.c. and 200 Mc/s resistivities of pure and metal-doped selenium have been studied as functions of temperature. The properties of materials in the two important micro-structures (colony and equiaxed) were distinguished. The influences of the metals Na, Cu, Ag, Mg, Zn, Cd, Hg, Ga, In, Tl, Pb, Sb, Bi, Te, Fe, Ni, Co, and Ce were noted.

723. HENKELS, H. W. **Electrical properties of selenium: Part I—single crystals.** *J. Appl. Phys.* **22**: 916–925, Jly. 1951.

The dark resistivity of crystals grown in a melt was studied as a function of axis orientation, temperature, field, and time of application of field. The large values found for thermoelectric power indicate hole conduction with a hole density of the

order of $10^{14}/cm^3$, the density decreasing with temperature increase above room temperature. Mobilities and activation energies were also determined.

724. HENKELS, H. W. **Thermoelectric power and mobility of carriers in selenium.** *Phys. Rev.* **77**: 734–736, illus., Mar. 1, 1950.

The thermoelectric power of single crystal and microcrystalline selenium has been investigated as a function of temperature with parameters of crystallisation temperature and oxygen content.

725. HERRING, C., GEBALLE, T. H. and KUNZLER, J. E. **Phonon-drag thermomagnetic effects in n-type germanium. I. General survey.** *Phys. Rev.* **111**: 36–57, Jly. 1, 1958.

In magnetic field and thermal gradient, a conductor develops a Nernst field and its thermoelectric power depends on the magnetic field. These two effects were measured for single-crystal 6-armed high-purity n-Ge samples up to 18,000 gausses from liquid-H to intrinsic-conduction onset temperature with the most detailed measurements near liquid-air temperature. Both the Nernst coefficient and the thermoelectric increment are additive in electron-diffusion and in electron anisotropic scatter by phonons moving from hot to cold; at low temperatures the latter phonon-drag terms predominate and contribute to low-field Nernst coefficient to counterbalance the negative electron-diffusion contribution. Thermoelectric increase with field resembles magnetoresistance in anisotropy and field-dependence. A model is given to elucidate the relations discussed.

726. HERSHTEIN, E. Z., SAVITSKAIA, T. and STIL'BANS, L. **Issledovanie termoelektricheskikh svoistv telluristogo svintza. (Investigation of the thermoelectric properties of lead telluride).** *Zhurn. Tekh. Fiz.* **27**: 2472–2483, Nov. 1957.

In Russian.

Trans. in *Soviet Phys. Tech. Phys.* **2**: 2302–2313, 1957.

Translation no. R-4017 also available at Special Libraries Association Translation Center, Crerar Library, Chicago, Ill., and in Infosearch Tech. Lit. Info. Serv. Russian Lit. Survey SEM-4-57; 5·1–5·15.

The effect of degeneracy and mechanism of scattering of the current carriers on the kinetic coefficient, i.e. on the thermo-emf and electron mobility (u) in PbTe was investigated.

727. HIDA, HAJIME. **Thermoelectric properties of cadmium-antimony alloys.** *Kanazawa Daigaku Kogakubu Kiyo*, **2**: 6–16, 1957.

In Japanese. English summary.

"Thermoelectric power n and the electrical conductivity σ of Cd-Sb alloy are greatest when Sb content is 52%. The alloy of this composition consists of CdSb with possible inclusion of some Cd_3Sb_2. The n of this CdSb decreases with rise of temperature but is still 160 μV/degree at 200°. The addition of 8% Bi and 9·2% of Sn, or 8% of Bi, 4·2% of Sn, and 0·3T of Ag is effective to increase the σ as much as twice without decreasing α. When this Cd-Sb alloy with these additives is combined with n-type $BiTe_2$, a temperature lowering of about 15° is obtained at a c.d. of 20 amp. by Peltier effect." *Chem. Abs.* **53**: 13703, 1959.

728. HOCHBERG, B. M. and SOMINSKI, M. S. **Electrical conductivity and thermoelectric characteristics of semiconductors.** *Physik. Z. Sowjetunion.* **13**: 198–223, 1938.

In German.

The TE power of the network Cu-semiconductor Cu was investigated for WO_3, V_2O_5, CuO, Se, MoS_2, Bi_2S_3, Tl_2S, as well as for cobalt oxide. For most of these semiconductors, parallel measurements of the thermo-emf and the electrical conductivity in dependence of temperature were carried out. In the case of Tl_2S the thermo-emf changes its sign depending on the concentration of the mixtures and the temperature. The results obtained are discussed in relation to the views on the diffusion of electrons and on positive "holes."

729. HOCKINGS, E. F. **The thermal conductivity of silver antimony telluride.** *Phys. & Chem. Solids.* **10**: 341–342, Aug. 1959.

Thermoelectric measurements showed it to be a p-type, non-degenerate semiconductor.

730. HOGARTH, C. A. **Some conduction properties of the oxides of cadmium and nickel.** *Phys. Soc. Proc.* **64**: 691–700, Aug. 1, 1951.

Results of measurements of electrical conductivity and thermoelectric power of CdO and NiO at temperatures up to 500°C and at various pressures of the surrounding oxygen are shown graphically; they are in general agreement with theory.

731. HOGARTH, C. A. **Some conduction properties of the oxides of zinc and copper.** *Z. Physik. Chem.* **198**: 30–40, Oct. 1951.

In German.

Electrical conductivity and thermoelectric power of ZnO and Cu_2O were measured as functions of both temperature and oxygen pressure, and were found to be in general agreement with theories previously proposed. Measurements of the thermoelectric power of CuO indicate that this substance is an excess semiconductor, but its variation with oxygen pressure is in the opposite sense to that expected for such a material. Possible reasons for the discrepancies between theory and experiment are offered.

732. HOGARTH, C. A. **The variation with vapour pressure of the properties of certain electronic semi-conductors.** *Phil. Mag.* **39**: 260–267, Apr. 1948.

Formulas are given, and compared with experimental results, for the variation with vapour pressure of the Hall effect and thermoelectric power of semiconductors having an ionic lattice structure.

733. HOLMES, R. M. **The thermoelectric properties of sputtered films of gold, platinum, and**

palladium and of solid palladium containing occluded hydrogen. *Phys. Rev.* **22**: 137–147, illus., Aug. 1923.

Purpose of the investigation was to compare the thermoelectric power of a film couple with that of the solid metals from which the films were sputtered. The results obtained suggested the investigation also of the effect of occluded hydrogen upon the thermoelectric properties of solid palladium.

734. HOKHBERG, B. M. and SOMINSKII, M. S. **An investigation of the electrical conductivity and the thermoelectric properties of semiconductors.** *Zhurn. Eksp. i Teor. Fiz.* **7**: 1099–1104, 1937.

In Russian.

German trans. in *Physik. Z. Sowjet.* **13**: 198–223, 1938.

For abstract see *Chem. Abs.* **32**: 6144, 1938.

735. HORAK, JAROMIR; MACHOVEC MOJMIR and KOSEK FRANTISEC. **Zinc telluride as a semiconductor.** *Czechoslov. J. Phys.* **7**: 468–475, 1957.

In Russian.

The lattice constant for ZnTe, determined by the Debye-Scherrer method, was 6·085 A. The electrical conductivity of vacuum-deposited films on Cu substrates decreases with time and with rise in temperature. An activation energy of 0·25 e.v. was calculated for the range 0°–140°C. When sintered compacts were heated between Cu electrodes, the warmer contact had negative polarity, and the average value of the thermo-emf at 20°–50°C was ~0·5 mV/°C. The specimens therefore showed p-type conductivity.

736. HORNBECK, J. W. **Thermal and electrical conductivities of the alkali metals.** *Phys. Rev.* **2**: 217–240, Sept. 1913.

Considers thermoelectric and magnetic properties.

737. HORNE, R. A. **Effect of oxide impurities on the thermoelectric powers and electrical resistivities of bismuth, antimony, tellurium and bismuth-tellurium alloys.** *J. Appl. Phys.* **30**: 393–397, figs., Mar. 1959.

The thermoelectric powers of bismuth and antimony are only slightly altered by the presence of Bi_2O_3 and Sb_2O_3 respectively, and the electrical resistivities are increased. The thermoelectric power of tellurium, however, is extremely sensitive to TeO_2 impurities. Bismuth tellurium alloys show greatest sensitivity to oxide impurities when their composition is in the range corresponding to Bi_2Te_3. The thermoelectric powers of these materials depend in detail on the manner in which the thermal gradient is applied during measurement.

738. HUET, PIERRE and COLOMBANI, ANTOINE. **Temperature electric resistance curves for thin films of bismuth.** *Acad. Sci. Paris. Compt. Rend.* **244**: 865–868, Feb. 11, 1957.

In French.

Study of variation of resistance showed both reversible and irreversible modifications as well as semiconductor and metallic states. Three ranges of thickness studied; temperature coefficient curves in relation to thickness were traced.

739. HUGHES, L. E. C. ed. **Electronic engineer's reference book.** 1311 p., illus., London, Heywood & Co., 1958.

Thermoelectricity, p. 411–413, includes table of thermoelectric power values of various metals.

740. HUNTER, M. A. and BACON, J. W. **Thermoelectric force of some alloys.** *Electrochem. Soc. Trans.* **33**: 183–196, 1918.

Emf data are given for some binary and ternary alloys of iron, nickel and copper, with chromium and manganese.

741. HUTCHINS, C. C. **Thermoelectric heights of antimony and bismuth alloys.** *Am. J. Sci.* **148**: 226, 1894.

Experiments are made to determine which combination of these alloys produce the highest emf.

742. HUTSON, A. R. **Electronic properties of ZnO.** *Phys. & Chem. Solids.* **8**: 467–472, 1959.

Proceedings of 1958 International Conference on Semiconductors. Hall effect measurements on doped, n-type single-crystals of ZnO have yielded: a density-of-states mass of 0·5m, a shallow donor ionisation energy of 0·05 e.v. and a temperature dependence of mobility. An effective mass of 0·27m is derived from the donor binding energy. It is used in the computation of the optical-mode scattering, which, together with some acoustical-mode scattering fits the mobility data. Thermoelectric power measurements show the presence of a large phonon-drag (Q_p) contribution. The Q_p saturation effect yields an effective inertial mass of 0·07m, and it is shown that it is approximately isotropic. Magnetoresistance measurements show that there must be at least 12 valleys in the ZnO conduction band and that the valleys are not greatly anisotropic. The small inertial mass is compatible with the density-of-states mass and the 12 valleys of small anisotropy; however, the donor binding energy and the optical-mode scattering both seem to require an effective mass larger by a factor of 4. A tentative model is suggested which might resolve this difficulty.

743. HUTSON, A. R. **Semiconducting properties of some oxides and sulfides.** *In* Semiconductors, N. B. HANNAY, ed., p. 541–599, New York, Reinhold, 1959. (*Am. Chem. Soc. Monograph Series* 140).

Electrical conductivity, Hall effect, thermoelectric power; materials considered include: barium oxide, magnesium oxide, cadmium sulfide, cadmium telluride, lead sulfide, lead selenide, lead telluride.

744. IHARA, MASAYOSHI, *et al.* **The electromotive force between refractory oxides and molten glass.** *Yogyo Kyokai Shi.* **67**: 21–27, 1959.

In Japanese.

"The emf of the following cell was determined

at 1000°; Pt | solid oxide | —molten glass | Pt. As the glass, Na silicate, K silicate, common window glass, Pb glass, and Borosilicate glass were used. As the solid oxide kaolin, SiO_2, Al_2O_3, ZrO_2, CaO, MgO, BaO and ZnO were used. When the emf is plotted against the ratio of the radius of the cation of the solid oxide to the charge of that cation a straight line is obtained except for the case of ZnO." *Chem. Abs.* **53**: 11957, 1959.

745. INGLITSYN M. I. **On the electric properties of polycrystalline selenium.** *Zhurn. Tekh. Fiz.* **22**: 885–887 Apr. 1952.

In Russian.

Letter. Chemically pure Se was crystallised under 60 to 80 kg/cm² and constant temperatures ranging from 117° to 218°C. Specific electric conductivity differential thermoelectromotive force and Hall's constant were investigated between −180° and 200°C. It was found that the dissociation energy depends on the crystallisation temperatures. Within −180° and 200°C Hall's constant is practically independent of temperature but electric conductivity increases exponentially with temperature. Measurements of thermoelectromotive force confirms that the concentration of carriers of current (holes) is independent of temperature, which is not in accordance with the zone theory of semiconductors. It is, however, in agreement with results obtained on monocrystals of Se.

746. IGNAT'EV, E. A. and KOT, M. V. **Electrical conductivity and thermoelectromotive force of alloys of antimony and selenium.** *Uchenye, Zapiski Kishinev. Univ.* **24**: 19–24, 1956.

In Russian.

"Alloys were investigated containing 37·6–46·4% Sb, prepared by melting Se (99·99% pure) and Sb (99·999%) pure in vacuo at 10^{-3} mm Hg and annealing at 200° for 10 hours. Electrical conductivity and thermo-emf were measured of the samples in the range from room temperature to 200°. The compound Sb_2Se_3 possesses a hole mechanism of electric conductivity at both an excess of Sb and an excess of Se. The differential thermo-emf of the compound at room temperature was about $1{\cdot}2\times10^3$ μV/° and dropped sharply in the presence of Sb impurity." *Chem. Abs.* **53**: 3892, Mar. 10, 1959.

747. IOFFE, A. F. and IOFFE, A. V. **Correlation of thermal conductivity of semiconductors with electron mobility.** *Zhurn. Tekh. Fiz.* **24**: 1910–1911, Oct. 1954.

In Russian.

A table is given of corrected calculated values of thermal conductivities of C, Si, Ge, PbS, and Te, and of the mean free paths of phonons and electrons, together with experimental results.

748. IOFFE, A. V. and IOFFE, A. F. **Certain regularities in the values of the thermal conductivities of semiconductors.** *Akad. Nauk. SSSR. Dok.* **97**: 821–822, 1954.

In Russian.

Thermal conductivities (x) were determined for atomic and ionic crystal lattices and the relation of x to the atomic weight or the average atomic weight of the components was studied. Ionic crystals for which A_1/A_2 is less than 1·5 (where A_1 and A_2 are atomic weights of components) have a greater themal conductivity than those for which A_1/A_2 is over 1·5. x decreases with an increase in atomic weight, and with an increase in the ration A_1/A_2. Semiconductors considered include the alkali halides, AgCl, AgBr, TlCl, TlBr, diamond, Si, Ge, GaSb, and InSb.

749. IOFFE, A. V. and IOFFE, A. F. **Influence of additions on thermal conductivity of semiconductors.** *Akad. Nauk. SSSR. Dok.* **98**: 757–759, 1954.

In Russian.

The magnitude of the nonelectronic part of the thermal conductivity of semiconductors is determined by propagation of phonons and their scattering at the lattice points. For lattices containing foreign atoms (I), an equation is derived: $k_0/k = 1 + Nn\lambda_0/N_0a$, where k_0 and k are the corresponding thermal conductivities of the pure and modified semiconductors, respectively; N_0 and N are number of atoms per cc; n is coefficient in the equation $S = na^2$, where S is scattering cross-section and a is the lattice constant; λ_0 is free path of phonons in the lattice of the pure semiconductor. The value of $n \leq 1$ holds if (I) substitute for the regular atoms and $n \geq 1$ if (I) place interstitially. In some cases, $n \leq 0$; this may be caused by (I) placed in the positions of lattice defects. In cases of ordering or coagulation of (I), corrections to the equation are required. Applicability of the equation to the PbSe-PbTe system and to solid solutions of Sb and Si in Ge is demonstrated; in both cases, n is about 1. In AlSb or GaSb, n was 3 for addition of Te and 15 for addition of Se; other foreign atoms resulted in $n \leq 1$. Thus, the equation should be considered on the basis of specific properties of the (I) introduced.

750. IOFFE, A. V. and SINANI, S. S. **The heat conductivity of the oxides of the elements of the second group of the periodic system.** *Zhurn. Tekh. Fiz.* **25**: 1659–1661, 1955.

In Russian.

Thermal conductivity (x) measured from 5×10^3 to 10×10^3 atmospheres. At such pressures, original crystals are compressed to 50 to 81% of their original volume and, to get comparative values, all the values measured were recalculated for a compression to 80% of original crystal mass. Values for BeO and MgO scatter heavily, as shown by the $x.10^3$ values obtained: BeO–33; MgO–13; CaO–28; ZnO–20·2; SrO–15·8; CdO–9·3; BaO–6·0; and HgO–3·7 and the percent deviations from these averages are: for BeO, 30; MgO, 21; CaO,5; ZnO, 1; SrO, 3; CdO, 4·5; HgO, 5 (all plus or minus). For BaO, the measurements are to different to give a reliable value for the deviation.

751. IOFFE, A. V. and IOFFE, A. F. **Thermal conductivity of semiconductors.** *Akad. Nauk. SSSR. Ser. Fiz. Izvest.* **20**: 65–75, 1956.

In Russian.

Trans. in *Bull. Acad. Sci. USSR. Ser. Phys.* **20**, 1956.

Heat conduction in semiconductors is by phonon and electron conduction. For electric conductivity below 100 (ohm-cm)$^{-1}$, heat conductivity by electrons can be neglected, but it is considerable for electric conductivity over 100 (ohm-cm)$^{-1}$. Results shown for thermal conductivity in the region 1000–4500 (ohm-cm)$^{-1}$. Interaction of phonons and electrons is discussed. The thermal conductivity of phonons decreases with atomic weight and also depends on the bands and lattice type. The presence of impurities and crystal defects also decreases the number of phonons, as shown on mixtures: Si + Sn, Si + Ge, and PbS + PbTe. Substances best suited for thermocouples are those with the highest ratio of electron mobility to thermal conductivity. Different mechanisms leading to increased thermal conductivity in semiconductors at high temperatures, observed by different authors, are discussed.

752. IRIE, T., UNO, R., YOSHIDA, S. and SHINOHARA, K. **On the electrical properties of the polycrystalline boron. II,** *Tohoku. Univ. Res. Inst. Sci. Rept.* **47**: 223–227, Dec. 1953.

The temperature dependency of the thermoelectric power has been investigated over the temperature range from 100° to 800°K on polycrystalline boron samples. The thermoelectric power of the sample prepared in hydrogen atmosphere increases proportionally with the logarithm of absolute temperature in the measured temperature region, and that prepared in vacuum shows similar behaviour at least up to 600°C above room temperature. Such behaviour is expected when the sample is an impurity semiconductor having so small activation energy that all the impurity centres are ionised and yet intrinsic conduction does not appear.

753. ISHIGURO, K., SASAKI, T., ARAI, T. and IMAI, I. **Optical and electrical properties of tin oxide films.** *Phys. Soc. Japan. J.* **13**: 296–304, Mar. 1958.

The observed Hall effect and Seebeck effect show that the specimens used are n-type conductors whose carrier density is 10^{19} to 10^{20} cm^{-3}. The optical measurements made it clear that the fundamental energy gap was about 4 eV and the plasma frequency of the conducting carriers lie in the near infrared region. By comparing the observed optical transmission and reflection with the theoretical values, which can be calculated from the electrically measured constants, the effective mass of the carriers was determined to be about 1/5 of the free electron mass. To satisfy the thermoelectric power relation with this small effective mass, it must be assumed that the Coulomb scattering of impurity ions is the predominant scattering mechanism in transparent conducting tin oxide films.

754. IURKOV, V. A. and ALEKSEEVA, N. E. **Termoelektricheskie svoistva splavov Cd-Sb. (Thermoelectric properties of Cd-Sb alloys).** *Zhurn. Tekh. Fiz.* **26**: 911–912, 1956.

In Russian.

Translation in *Soviet Phys. Tech. Phys.* **1**: 911–912, 1956.

This article describes an experimental research on the thermoelectrical properties of Cd–Sb alloys with various Sb-content. The main purpose of the experiments was to obtain a general curve expressing the relationship between the thermal electromotive force and the composition of the alloys. The specimens were prepared by melting Cd and Sb in vacuo. During measurement of the thermoelectric force, specimens were held between two copper blocks at constant temperatures of 10 and 100°C. The results obtained with 18 specimens of varying Sb-content are illustrated by a curve in Figure 1 and are briefly discussed. It is stated that large magnitudes of the thermoelectric force in Cd-Sb alloys, and a sharp maximum in the thermoelectric force—composition diagram, permit the expectation that the energy spectrum of Cd-Sb alloys be of a structure which is usual for semiconductors. For a final conclusion, however, investigation is required of the temperature dependence of Cd-Sb electroconductivity.

755. IVANOV, G. A., and MOKIEVSKII, L. I. **Thermoelectric properties of bismuth.** *Leningrad Gos. Pedagog. Inst. Uchenye Zapiski.* **17**: 88–92, 1957.

In Russian.

"Experiments are described and results are given of the accurate determination of the relationship of the coefficient of thermal-emf α of Bi to the difference of the temperatures at the ends of the specimen $\Delta = t$ and the relationship α to the general temperature.

The investigations were carried out on Bi of different purity; on commercial Bi (BiTi), on Bi with traces of Pb, Cu, Ag and Ga (BiC) and on Bi obtained from BiC by means of zone refining. The measurements were carried out on cylindrical monocrystals 2–20 cm long and 3–4 mm in diameter. The thermo-emf was measured relative to Cu. It was found that at Δt 0·25–8 α does not depend on Δt. To verify the relationship of α to Δt in the case of an already smaller Δt a special experiment was carried out in which 20 measuring probes were attached to a monocrystal 12 cm long. By slow heating of one of the ends (2° in the course of 10–12 hours) a linear distribution of temperature along the length of the specimen was attained. It was established that when Δt is from 0·0007 to 0·5 α also remains constant. When the temperature increases from 20° to 230° α gradually decreases by 25%." *J. Abs. Metall.* nos. 10, 11, 12, 1957.

756. IVANOV, G. A. and MOKIEVSKI, L. I. **Thermoelectric properties of bismuth.** *Zhurn. Tekh. Fiz.* **26**: 1343–1344, June 1956.

Contrary to the results obtained by Sato, it was found that the coefficient of the thermo-emf of bismuth remains constant for temperature differences across the specimen greater than 0·01 C.

757. JAFFRAY, J. and CARIAT, J. **Some physical properties of nickel amalgams.** *Acad. Sci. Paris. Compt. Rend.* **231**: 1128–1130, Nov. 20, 1950.

In French.

Measurements of resistance, thermoelectric properties and specific heat of dilute Ni amalgams have shown that in each case there is an abrupt irreversible change occurring near 220°C. These results are in agreement with those of Bates and others for resistance and susceptibility. It is suggested that the phenomena may be associated with a change from hexagonal to cubic Ni since Michel has found that a non-ferromagnetic hexagonal form with C or N in the lattice changes irreversibly to a cubic ferromagnetic form at 210° or 190°C respectively.

758. JAMES, C. M. L. **Thermoelectric power of some bismuth alloys.** *Am. Inst. Mining Met. & Petrol. Engrs. Trans.* **212**: 661–663, Oct. 1958.

The thermoelectric power of polycrystalline bismuth at room temperature as a function of the temperature gradient, at higher temperatures up to 207°C and of air cast samples of Bi–Tl, Bi–In, and Bi–Mg alloys at room temperature are reported.

759. JAN, J. P., PEARSON, W. B. and TEMPLETON, I. M. **Thermoelectricity at low temperatures. V. The suitability of lead as a standard reference material.** *Can. J. Phys.* **36**: 627–631, May 1958.

Concludes that lead seems to be a most suitable reference material against which measurements of the absolute thermoelectric power of metals and alloys can be made.

Abstract also in *Chem. Abs.* **52**: 13344, Aug. 25, 1958, and *Phys. Abs.* **61A**: 5013, Aug. 1958.

760. JOHANSEN, H. A. and MILLER, R. C. **Seebeck coefficient of yttrium from 0° to 1000°C.** *J. Less-Common Metals.* **1**: 331–332, Aug. 1959.

A specimen of yttrium-swaged rod 1/16 in. in diameter and 16 in. long was made available for examination by U.S. Bureau of Mines. The rod was swaged from material with an yttrium analysis of about 99·7%. Principal impurities were oxygen, iron, chromium and copper.

A schematic diagram of the apparatus is shown, and a table gives the Seebeck coefficient and thermal emf.

761. JOHN, W. G. and EVANS, E. J. **The Hall effect and some other physical constants of alloys. The antimony-silver series of alloys.** *Phil. Mag.* **22**: 417–425, 1936.

The thermoelectric power of antimony-silver alloys varies with composition between +40 and −7 microvolts per degree centigrade.

762. Joint Publications Research Service. New York, N.Y. **Some fundamental problems of development of thermo-electric power plants.** USSR, by P. YA. TYURIN. 26 p., Feb. 14, 1960. (JPRS 2226).

The dependence of an economically expedient level of initial steam parameters in thermoelectric power plants on the unit power of aggregates is examined, as well as the problem of the distribution of electric power stations in relation to fuel bases. The selection of a power reserve in power systems is substantiated. (Photocopies of this report may be purchased from L.C. Photoduplication service).

763. JONES, H. **The valency of the transition metals in some binary and ternary alloys.** *Phil. Mag.* **44**: 907–912, 1953.

The change of valency of transition metals atoms in different alloy systems is considered. Reasons for expecting the valency to decrease as the electron concentration in the conduction band increases are given. Rough agreement with the experimental results of Haworth and Hume-Rothery is obtained in the case of Mn, Fe, and Co. Suggestions are made to account for the apparent fractional valency of Ni.

764. JUSTI, E., NEUMANN, G. and SCHNEIDER, G. **Thermoelektrische untersuchungen an $Zn_xCd_{1-x}Sb$ (Thermoelectric investigations of $Zn_xCd_{1-x}Sb$).** *Z. Physik.* **156**: 217–234, Sept. 23, 1959.

In German.

This is a discussion of thermoelectric properties of zinc antimonides and cadmium. For abstract see *Chem. Abs.* **54**: 996g, Jan. 25, 1960.

765. JUZA, ROBERT and BAR, KARL. **Conductors and semiconductors among the phosphides of the first and second subgroups.** *Z. Anorg. u. Allg. Chem.* **283**: 230–245, 1956.

In German. Not examined.

"The specific resistance at 0° in Ω cm., the temperature coefficient of the resistance in degree^{-1}, the differential thermal potential vs. Ag in mV/degree, and $\triangle\varepsilon$ in eV are respectively, for Cu_3P $1{\cdot}4\times10^{-4}$, 0·0022, 0·0072, and –; for two samples of Cu_2P 57·5 and 378, – and –, 0·80 and 0·69, and 0·40 and 0·31 above 219°K and 0·35 and 0·26 below 219°K; for Ag_2P 0·30–0·33, not linear, 0·48, and –; for Au_2P_3 $1{\cdot}24\times10^{-3}$, $2{\cdot}8\times10^{-3}$, –, and –; for Zn_3P_2, $1{\cdot}0-16\times10^{3}$, –, 1·0–1·2, and 0·49–0·61; and for Cd_3P_2 $3{\cdot}5\times10^{-3}$, $3{\cdot}9\times10^{-3}$, –0·15, and –. A plot of the differential potential vs $\log\rho_0$ gives a straight line as expected for semiconductors. Cu_3P is almost a metallic conductor. Cu_2P a p-type semiconductor below 219°K, and a self-conductor above 219°K., Ag_2P a transistor, and Zn_3P_2 a p-type semiconductor with properties strongly dependent on preparation condictions, surrounding atmosphere, and illumination. In the solid solutions formed between Zn_3P_2 and Cd_3P_2 the semiconductor properties of Zn_3P_2 are retained at 50% Cd_3P_2 but ρ_0 and $\triangle\varepsilon$ are greatly decreased at 75% Cd_3P_2." *Chem. Abs.* **50**: 11099, 1956.

766. KONOROV, P. P. **Electrical properties of bismuth chalcogenides, Pt. 1, Electrical properties of bismuth sulfide, Bi_2S_3.** *Zhurn. Tekh. Fiz.* **26**: 1126–1128, 1956.

In Russian.

Trans. in *Soviet Phys. Tech. Phys.* **1**: 1100–1102, 1957.

Properties measured on polycrystalline material compressed at 2500 kg/cm² and 300°C. Conductivity measured in the range room temperature to 600°K. The specific conductivity varied from $3{\cdot}4 \times 10^{-4}$ to 1×10^{-3} (ohm-cm.)$^{-1}$. Activation energy was 0·17 eV below 400°K and 1 eV above 400°. Coefficient of thermo-emf was 1300 μV/°C. at room temperature and corresponded to electronic conduction. Excess Bi increases conductivity to 10 (ohm-cm.)$^{-1}$ and decreases thermo-emf to 140 μV/°C. The mobility is low, of the order, of a few sq.sm. per v.-sec., which is attributed to a predominance of ionic bands. Width of the forbidden gap is 1 eV.

767. KONOROV, P. P. **Electrical properties of bismuth chalcogens. II. Electrical properties of bismuth selenide Bi_2Se_3.** *Soviet Phys. Tech. Phys.* **1**: 1365–1370, Jly. 1956.

English translation of Russian article.

768. KONOROV, P. P. **Electrical properties of bismuth. Pt. 2. Electrical properties of bismuth selenide. Pt. 3. Electrical properties of bismuth telluride.** *Zhurn. Tekh. Fiz.* **26**: 1394–1405, 1956.

In Russian.

Electrical conductivity, Hall constant and coefficient of thermoelectric emf of polycrystalline and single crystal samples of Bi_2Se_3 investigated over the range 20–700 K. and occasionally at liquid air temperatures. Same measurements on Bi_2Te_3.

769. KONOZENKO, I. D. and USTLYANOV, V. I. **Electrical properties of the lead-antimony system.** *Zhurn. Tekh. Fiz.* **27**: 1686–1684, Aug. 1957.

In Russian.

Alloys containing 11, 12, 13, 14 and 37 wt. %, i.e. up to 50 atm % Sb were investigated. Spectrographically pure Sb and Pb with < 0·001% Sn and Cu were used for the preparation of the experimental samples melted in evacuated glass ampoules. The electrical conductivity of all the studied alloys and their thermo-emf against Cu were measured at 0°–300°C. The Hall effect and the sign and concentration of the current carriers were determined at room temperature only, with the exception of the 50 at. % Sb alloy in which the temperature dependence of the Hall effect was studied at 0°–300°C. The experimental results are shown in the form of graphs and are correlated with the constitution of Pb-Sb alloys.

770. KOPATA, Z. **Concerning the problem of the effective mass of electrons and holes in germanium.** *Zhurn. Tekh. Fiz.* **26**: 2451–2458, Nov. 1956.

In Russian.

The authors subject to theoretical investigation the structure of the conductivity zone of germanium by considering the temperature dependence of the thermoelectromotive force and the concentration of current carriers in the region of admixture conductivity. (*Rev. Met. Lit.* **14**: 74–P, 1957).

771. KORENBLIT, L. L. and KOLESNIKOV, A. P. **Magnetic properties of Mg_2Sn.** *Zhurn. Tekh. Fiz.* **26**: 941–944, 1956.

In Russian.

Earlier experiments are repeated over a temperature range of 20–210°C with alloys of very high purity (not more than 0·0% Pb or Sb) with approximately the same results as Boltaks. Also measured were the electrical conductivity and thermoelectric emf. The Hall effect for one "impure" specimen was measured at room temperature. It is concluded that the results indicate that the paramagnetism of "impure" specimens is associated with the paramagnetism of free electron gas in the Mg_2Sn crystal.

772. KOSTER, WERNER and ROCHOLL, PETER. **Conductivity and Hall constants. I. Nickel-chromium alloys.** *Z. Metallk.* **48**: 485–495, 1957.

In German.

The electrical resistivity, Hall coefficient, thermo-emf, magnetic susceptibility, Vicker's hardness and Young's modulus of paramagnetic Ni–Cr alloys containing Cr 10–37 at. % were measured as a function of thermal and mechanical history. The results are discussed in relation to the collective electron theory of metals and it is considered that the number and mobility of the charge carriers are determined by the atomic groupings. The K-state is related to a short-range order changing the mean distribution of electrons and holes in the upper energy-bands.

773. KOT, M. V. **Electrical conductivity and thermal electromotive force of the intermetallic compound CdSb.** *Uchenye Zapiski Kishinev. Univ.* **24**: 3–10, Jan. 1956.

In Russian.

Electrical conductivity (E) and the thermal-emf of the intermetallic compound CdSb of near-stoichiometric composition was investigated. The original components contained Pb<0·001%. The measurements were carried out in the range 103–473°K. The compound CdSb is an extrinsic semiconductor with hole conductivity. It is assumed that covalent bonds exist between the atoms of the compound. By assuming hole conduction, it is supposed that excess Cd or Sb in the compound leads to formation of solid solutions. On the basis of hole conduction a qualitative explanation of temperature dependence of E and of thermal emf is given.

774. KOT, M. V. **Electroconductivity and thermoelectric force of the intermetallic compound ZnSb.** *Uchenye Zapiski Kishinev. Univ.* **24**: 11–18, 1956.

In Russian.

The electroconductivity and the thermo-emf

of Zn-Sb alloys containing 48–56 at. % Zn were measured in the range 250–625°K. The width of the forbidden zone of the compound ZnSb was 0·6e.v.

775. KOT, M. V. **Electroconductivity and thermo-emf of intermetallic compound SbZn.** *Ucheny Zapiski, Khurkovsky Univ.* no. **24**: 11–18, 1956.

In Russian.

Electroconductivity and thermo-emf of alloys of Zn and Sb containing 48 to 65 at. % Zn were measured in the range of 250 to 625 K. The width of the forbidden zone of the compound ZnSb was 0·6 e.v.

775. KOVAL'CHIK, T. L. and MASLAKOVETS, YU. P. **The effect of impurities on the electrical properties of lead telluride.** *Zhurn. Tekh. Fiz.* **26**: 2417–2431, 1956.

Translation in Infosearch Tech. Lit. Info. Serv. Russian Lit. Survey SEM-2-57: 8·1–8·18, figs., 1957.

Reports the results of measurement of electrical conductivity, thermal emf and current carrier concentration on PbTe specimens containing various impurities.

776. KOZYREV. P. T. **Equilibrium and non-equilibrium properties of polycrystalline selenium.** *Zhurn. Tekh. Fiz.* **27**: 35–44, 1957.

In Russian.

English translation in *Soviet Phys. Tech. Phys.* **2**: 27–34, 1957.

The temperature dependence of the equilibrium concentration of holes (n_∞) in Se was derived from measurements of thermal emf. Results agree with Henkels. For specimens with low mobility of charge carriers, the equilibrium electrical conductivity (σ_∞) increased with temperature (T) to a maximum at about 140°C, then fell. For specimens with high mobility, ρ_∞ fell monotonically with increase of T in a manner similar to n_∞. Results are discussed in relation to the suggestion that the grains in polycrystalline Se are separated by regions (possibly amorphous) of high resistivity.

778. KROGER, F. A., VINK, H. J. and VOLGER, J. **Temperature dependence of the Hall effect and the resistivity of CdS single crystals.** *Philips Res. Rpts.* **10**: 39–76, 1955.

D.C. dark conductivity and Hall effect of CdS crystals were measured from 25 to 700 K. The TE power of pure crystals and crystals doped with Ga and Cl was determined, while the insulating crystals CdS–Cl, Ag and CdS–Cl, Cu were examined for photoconductivity and low frequency capacitance.

Room temperature values of the TE power and the variation of Hall constant with temperature can be explained by an effective mass ratio m/m_0 of 0·2 to 0·3 (m_0 is the mass of a free electron in vacuo).

779. KROPSCHOT, R. H. and BLATT, F. J. **Thermoelectric power of cold-rolled pure copper.** *Phys. Rev.* **116**: 617–620, figs., Nov. 1, 1959.

The difference between the thermoelectric power of severely cold-rolled and well annealed pure copper has been measured between about 8°K and 320°K. The absolute thermoelectric power of the annealed and cold-worked samples were determined over the same temperature range by measuring the thermoelectric power of a thermocouple formed from annealed pure copper and pure lead. The thermoelectric power of cold-rolled copper is positive relative to annealed pure copper over the entire temperature range, and the effect of cold work is largest at very low temperatures where the thermoelectric power of annealed copper displays a pronounced minimum. Our results are in fair agreement with recent work by Powell and by van Ooijen.

780. KROPSCHOT, R. H. **The thermoelectric power of copper alloys.** *Dissertation Abs.* **20**: 1410, 1959. Michigan State University PhD thesis, 1959.

The following alloys—CuZn, CuGe, CuCd, CuIn, CuSn, CuSb—were prepared by melting the components in vacuum. All alloys contained approximately 99% copper. The thermoelectric powers of these copper alloys relative to pure copper have been measured over the temperature range 4·2°K to 340°K.

781. KUROV, G. A., SEMILETOV, S. A. and PINSKER, Z. G. **Electrical properties and real structure of germanium single crystal films prepared by evaporation in vacuo.** *Kristallografiya.* **2**: 59–63, 1957.

Translation in Infosearch Tech. Lit. Info. Serv. Russian Lit. Survey SEM-3-37: 13·1–13·9, illus., 1957.

Simultaneously with structural investigations, measurements were also made of the electrical properties of the films, namely resistivity, Hall emf and thermoelectric power.

782. LAGRENAUDIE, J. **Optical and electrical study of bismuth telluride, Bi_2Te_3.** *J. Phys. et Radium* **18**: 39A–40A, 1957.

In French.

Bi_2Te_3 purified by zone melting exhibited mostly p-type conduction; crystals near the edge of the ingot were type n if excess Te was used. The thermoelectric effect was: for type p, +230 microv./degree, for type n, −210 microv./degrees. Addition of I (1/300 of Te) produced homogeneous type-n(−150 μV/degree). Type p Bi_2Te_3 was converted to type n by compression; thin plates half compressed exhibited an n-p junction. From the infrared absorption threshold, the energy of activation was 0·19 e.v. The n was ≈8. The similarity of Bi_2Te_3 to PbTe was noted.

783. LAGRENAUDIE, J. **Study of the electrical properties of mercury telluride.** *J. Chim. Phys.* **55**: 175–176, 1958.

In French.

HgTe was obtained by heating the two elements in a sealed quartz tube at 650°C. The compound exhibits a negative thermo-emf (e)

of 130μV/°C. By replacing a part of the Hg, with Ag, giving Te-Hg^{1-a}-Ag^a, with $a=2\%$, a compound exhibiting a positive e of 145μV/°C is obtained. By slowly freezing the mixture Te-Hg^{1-a} Ag^a in a horizontal tube, a nonhomogeneous ingot is obtained which is of p-type in the zones which solidify first (e=120−145μV/°C) and of n-type in the zones which solidify last (e=−130μV/°C). Transparency studies on thin films, in the infrared region, show that the activation energy is ~0·15 eV. Electrical measurements at ~20°C, both on n- and p-types, show an electron mobility of 6000–25,000 cm^2/Vsec. The Kikoin photomagnetic effect was observed on 0·1-mm. samples of both types and the recombination velocity calculated as >100μsec. for p-type samples and even higher for n-type samples.

784. Lapp, G. B. and Maksimova, V. L. **Thermoeletric properties of some metals and alloys of the platinum group.** *Zhurn. Neorg. Khim.* **2**: 2589–2597, 1957.

In Russian.

The stability of the thermal emf (E) of Ir wire and Rh and Rh–Pt electrodes was studies. The maximum change in E of Ir heated in vacuo was during the first hour (−16·0 at 1800 and −26·0 m.v. at 2000°); it stabilized after 13 hours. The loss in weight was considerably lower when heated in A. Rh and Rh–Pt containing more than 10% Rh when heated with an electric current in vacuo exhibited "extinction," a drop of 150–200° with a rising current. Rh and alloys containing 30% Rh were more stable than alloys containing 6 and 40% Rh when heated at 1700–1800° in A. Powdered Al_2O_3, MgO and ThO_2 and protective BeO tubes did not affect E of 6, 13 and 30% Rh alloys at 1500°.

785. Lark-Horovitz, K., Middleton, A. E., Miller, E. P. and others. **Electrical properties of germanium alloys. II. Thermoelectric power.** *Phys. Rev.* **69**: 259, 1945.

Abstract only, reports results of study of thermoelectric power, Q of germanium alloyed with various metallic impurities as a function of temperature from −180°C to 650°C.

786. Lavine, J. M. **Ordinary hall effect in Fe_3O_4 and $(NiO)_{0\cdot75}$ $(FeO)_{0\cdot25}$ (Fe_2O_3) at room temperature.** *Phys. Rev.* **114**: 482–488, Apr. 15, 1959.

Room temperature Hall measurements on a synthetic single crystal of $(NiO)_{0\cdot75}$ $(FeO)_{0\cdot25}$ (Fe_2O_3) are reported. The thermoelectric power of the sample of Fe_3O_4 was also measured and verified that the sign of the charge carrier was negative. The ordinary Hall measurement of Fe_3O_4 suggests that the number of conduction electrons at room temperature is of the order of 3×10^{21}/cm^3, in rough agreement with Verwey's model.

787. Lee, J. A. and Hall, R. O. A. **Some measurements on the thermoelectric power of plutonium metal.** *J. Less-Common Metals* **1**: 356–361, figs., Oct. 1959.

The thermal emf of a plutonium-platinum thermocouple has been measured between 20°C and 630°C, and the absolute thermoelectric power of plutonium in its six allotropic modifications calculated over their stable temperature range. The implications of the results in relation to the form of the density of states/energy curve at the Fermi surface are discussed.

788. Lee, J. A., Evans, J. P., Hall, R. O. A. and King, E. **Some physical properties of the neptunium metal: III. The electrical resistivity and thermoelectric power of neptunium metal in the range 300–900°K.** *Phys. & Chem. Solids* **11**: 278–283, figs., Oct. 1959.

The electrical resistance of a sample of neptunium metal has been measured between 300° and 900°K, and the resistivity of neptunium in its three allotropic modifications calculated. A measurement of the thermal emf of a neptunium/platinum thermocouple has been made within the temperature-stable range of each allotrope, and the corresponding absolute thermoelectric powers calculated. The results are discussed briefly.

789. Leifer, H. N., Ellett, M. R., Cuff, K. F. and Krogstad, R. S. **Galvonomagnetic and thermomagnetic effects in PbTe.** *Am. Phys. Soc. Bull.* **4**: 362, Aug. 27, 1959.

Abstract only.

In an attempt to understand the scattering mechanisms in PbTe and similar semiconductors, magnetoresistance, thermomagnetic resistivity, Hall and thermoelectric measurements have been carried out in the temperature range of 300°K to liquid helium.

790. Lepoutre, G. and Dewald, J. F. **Thermoelectric properties of metal-ammonia solutions. II. The thermoelectric power of sodium and potassium solutions at −78° and the effect of added salt on the thermoelectric power of sodium at −33°. III. Theory and interpretation of results.** *Am. Chem. Soc. J.* **78**: 2953–2962, Jly. 5, 1956.

Measurements of the thermoelectric power of sodium and potassium solutions in liquid ammonia at −78° and of mixed sodium-sodium chloride solutions at −33° are reported. The results in dilute solutions show an anomalously large dependence of thermoelectric power on temperature and on concentration of salt, as well as a small but significant dependence on the nature of the metal ion.

791. Lepoutre, G. and Dewald, J. F. **The Thermoelectric properties of metal-ammonia solutions. III. Theory and interpretation of results.** *Am. Chem. Soc. J.* **78**: 2956–2962, Jly. 5, 1956.

Thermodynamic equations are derived for the thermoelectric power of metal-ammonia solutions which include the effects of electron-electron and electron-ion interactions. The previously reported

anomalies in thermoelectric behaviour of metal and metal-salt solutions are shown not to arise from these interactions, but rather from a large negative heat-of-transport of the electrons in these solutions ($Q_e^* = -0{\cdot}7$eV). This large negative heat-of-transport is accounted for on the assumption that electrons move through the solutions, even at high dilution, by a quantum tunnel process, rather than by the previously considered ionic, or conduction-band processes.

792. LEWIS, E. J. **Some thermal and electrical properties of beryllium.** *Phys. Rev.* **34**: 1575–1587, Dec. 15, 1929.

The thermoelectric power of beryllium against lead seems to vary linearly with temperature. However, at −50°C the graph of the thermoelectric power plotted against temperature shows a break. This, considered in connection with the results obtained for the temperature coefficient of resistance, suggests the probability of a change in allotropic form.

793. LEYERS, H. J. **The technical evaluations of thermoelectric effects (particularly in zinc-antimony alloys).** Dissertation, E.T.H. Zurich, No. 2557, 101 p., 1956.

In German.

"The efficiency of the thermoelectric element, when used as an electrical generator, a refrigerator, or a heat pump, is treated mathematically. The results of some experimental studies of Zn–Sb alloys are given." *Sci. Abs.* **60A**: 7933, 1957.

794. LI, J. C. M. **Thermoelectric power of [bismuth and] some bismuth alloys.** *AIME. Met. Soc. Trans.* **212**: 661–664, 1958.

The thermo-emf of polycrystalline 99·999% Bi at temperatures up to 207°C can be described by the equation $dE/T = 72 - 0{\cdot}042t\,\mu V/°C$, with t in °C. Addition of Ti to Bi produce three maxima in the dE/dT plot at ~ −5, 0 and −2μV/°C, at composition consistent with the composition of the Bi_5Tl_3, α, and *B* phases in the system. In the Bi-In system the dE/dT plot has a maximum (−5μV/°C) at the composition corresponding to BiIn, and a small minimum at the *B*– phase composition. In the Bi-Mg system dE/dT rises to ~ +45μV/°C at the composition corresponding to Mg_3Bi_2, and decreasing to ~ −25μV/°C at 30 wt. % Mg, rising again to ~ −5μV/°C at 60 wt. % Mg and then finally rising more slowly to the value for pure Mg.

795. LINDENBLAD, N. E. **Tellurium-bismuth-antimony thermoelectric elements.** U.S. Patent 2,762,857, Sept. 11, 1956.

Alloys suitable for a thermoelectric application containing Te 55–65, Bi 17–32, and Sb 8–23 mole %, at least one of Ag, Au, and Hg 0–0156 weight %, and at least one of S and Se 0–1·7 weight %, both weight %s are based on the total weight of Te, Bi, and Sb. Such alloys are of the p-type thermoelectric class. In an electric circuit with an alloy such as PbTe under an applied potential they produce heating at the negative and cooling at the positive connection. A typical alloy consists of Te 60, Bi 20 and Sb 20 mole-% and Ag 0·28 and Se 0·56 weight-%. Its thermal emf is 140 microvolts per degree and its resistivity is 0·0005 ohm-cm. The added impurities Ag, Au, and Hg decrease the resistivity without adversely affecting the thermal emf, while S and Se increase the thermal emf without adversely affecting the resistivity.

796. LINDENBLAD, N. E. **Thermoelectric amalgams of antimonides of cadmium and zinc.** U.S. Patent 2,758,146 (to RCA), Aug. 7, 1956.

Amalgamation of CdSb and ZnSb increases their effective thermoelectric power. Optimum results are achieved when Hg is added to CdSb which already departs slightly from perfect stoichiometry, while ZnSb gives the best results when Hg is added to the pure compound. Hg not only decreases the resistivity of the materials but also increases their thermoelectric force. Preparation of the alloys is also facilitated and their physical strength improved. Preferred materials consist of CdSb or ZnSb alloyed with 2% Sb and 2·5% Hg. This alloy is (sic) thermoelectric junction with Pb has an effective thermoelectric power of about 130 microV., as compared with a thermoelectric power of about 110 microv. obtainable with an alloy of CdSb and 2% Sb without Hg. The Hg-containing alloy exhibits a substantially lower electric resistance than the Hg-free alloy.

797. LINDER, E. G. **Thermoelectromotive force in single zinc crystal wires.** *Phys. Rev.* **26**: 486–490, 1925.

Zinc crystals made by the Czochralski method yielded 650 microvolts with respect to copper when a temperature gradient of 290°C was maintained.

798. LIPATOVA, V. A., GEL'D, P. V. and DAVYDOV, K. N. **Thermoelectric properties of alloys of silicon with iron, chromium and manganese.** *In* Fiz. Khim. Osnovy Proiz-va Stali, p. 387–398, Moscow, Akad. Nauk. SSSR., 1957.

In Russian. Not examined.

"A study was made of the relationship between composition and thermoelectric emf, E, in Fe-Si, Cr-Si and Mn-Si alloys. Measurements were made on a Korzh apparatus (Zavod. Lab. **14**: 107, 1948). For Fe alloys with 4–6% Si, E is negative and small (up to 1·58 mV at 100°C). With increasing Si content E decreases, reaching zero at 17% Si. From 17 to 59% Si, S is positive, small in value and slightly dependent on alloy composition. Change in Si content from 57 to 59% causes E to change from 0·67 mV at 100°C to zero. On further increasing the Si content, E becomes negative and its magnitude increases. For cast Si (99·2%) E is 51–60 mV at 100°C. In Si-Cr alloys, E for pure Cr is + 0·6 mV at 100°C. With increasing Si content, E falls, changes sign, and at 10% Si reaches (–0·9–1·0) mV at 100°C; beyond

this E falls, maintaining a negative value. On the E curve for Mn–Si alloy, singular points are observed which correspond to stoichiometric compositions and the stability ranges of chemical compositions. A correlation is revealed between the E-curves and melting point curves for the systems. It is suggested that alloys with negative E have a major proportion (by volume) of crystallite with electron conductivity. E was studied for the various modifications of ζ-phase Fe–Si. Its low temperature modification has a positive E of 0·3–0·6 mV at 100°C, depending slightly on the Si content. The ζβ modification, in equilibrium at 650–908°C is easily quenched at room temperature is characterised by high E value, highly dependent in magnitude and sign, on the Si content. The E of ζ (920°C) depends in magnitude and sign on the alloy composition." *J. Abs. Metall.* no. **2**: 22, 1958.

799. LIPATOVA, V. A., GEL'D, P. V. and DAVYDOV, K. N. **Thermoelectric properties of iron-silicon, chromium-silicon, and manganese-silicon alloys.** *Ural. Politekh. Inst. im S.M. Kirova, Sbornik Trudy.* **72**: 105–120, 1957.

In Russian. Not examined.

"The thermal emf of the above alloys with different concentrations of Si (from 0 to 100%) was measured in relation to Cu. For Fe-Si alloys with 4–6% of Si, it is equal to 1·58 mV/100°. Upon the increase of Si concentration, its value decreases and it reaches 0 for an alloy containing approximately 17% Si. All samples containing from 17 to 59% of Si have positive thermal emf (the lowest value being 0·2 vm./100°). A further increase in the concentration of Si for an alloy that contains 57% Si affects sharply the thermal emf and it changes from 0·67 mV/100° to 0 on the increase of Si concentration from 57 to 59%. No similar results were obtained in the measurements of the thermal emf for samples containing > 60% Si. The thermal emf of a cast Si sample (99·2%) is negative, and its value is 51–60 mV/100°. Between the thermal emf and melting point of Fe–Si (with different Si content) there exists a certain correlation, e.g. starting with 8–10 at. % Si, for every increase of melting point of the alloy there is a corresponding decrease of thermal emf and vice versa. The thermal emf of pure Cr is 0·6 mV/100° and it changes to negative on addition of 10 wt. % of Si to it, its numerical value being 0·9–1·0 mV/100°. On further addition of Si, the sign changes to positive and it is equal to 16 mv./100° when the concentration of Si reaches 52%. The thermal emf decreases rapidly on addition of Si over 52%. The curve of the thermal emf of Mn-Si alloys has characteristic points that correspond to Mn_3Si, Mn_5Si_3, and it is more steady for compounds Mn_2Si_3 and $MnSi_2$. The highest positive value of the thermal emf (11 mV/100°) occurs for the Mn–Si alloy containing 45% Si. A further addition of Si rapidly decreases the thermal emf, changing it from positive to negative. In contrast to Fe–Si alloys, the Mn–Si and Cr–Si alloys do not have a simple correlation between the thermal emf and the melting point." *Chem. Abs.* **53**: 13954, 1959.

800. LIPATOVA, V. A., GEL'D, P. V. and DAVYDOV, K. N. **Thermoelectric properties of silicon alloyed with iron, chromium and manganese.** *Inst. Met. im A. A. Baikova, Trudy* 3-*ei Konf.* 1955, p. 387–398 (Pub. 1957).

In Russian.

For English summary see *Chem. Abs.* **54**: 7263, Apr. 25, 1960.

801. LOEBNER, E. E. **Thermoelectric power of carbons.** *Phys. Rev.* **91**: 243, Jly. 1, 1953.

A single batch of carbon rods was used. They were heat-treated to progressively higher temperatures and investigated after each heat-treatment. Curves for the thermoelectric power exhibit a shallow minimum (around 1300°C) and a maximum. Resistivity curves show the well-known plateau.

802. LOEBNER, E. E. **Thermoelectric power, electrical resistance, and crystalline structure. of carbons.** *Phys. Rev.* **102**: 46–57, Apr. 1, 1956.

TE power and electrical resistivity of soft and hard carbons investigated as functions of heat treatment, temperature (1000° to 3100°C.) at 3 ambient temperatures, 90°, 305°, and 573°K. Report on measurements on soft and hard carbons, the influence of heat-treated temperature was investigated.

803. LOEBNER, E. E. **Thermoelectric power of carbons and graphite.** *Phys. Rev.* **84**: 153, Oct. 1, 1951.

Letter. The thermoelectric power of baked carbon rods was found to vary greatly with the temperature to which they had been baked. The theory is discussed.

804. LOEBNER, E. E. **Thermoelectric power, electrical resistance and crystalline structure of carbons.** *Phys. Rev.* **102**: 46–57, Apr. 1, 1956.

Ph.D. thesis. University of Buffalo, 1955.

The thermoelectric power and the electric resistance of soft and hard carbons were investigated as functions of heat-treatment temperatures. The crystalline structure was studied by means of X-ray powder diffraction technique.

805. LOW, G. G. E. **Some experiments on semiconducting powders.** *Res.* **7**: S22, Apr. 1954.

The thermoelectric powers of n-type Ge and PbS and of p-type Ge, Si and PbS were measured for various grain sizes and the results are shown graphically. With decreasing grain size, both magnitude and sign of the thermoelectric power changed for n-type materials, but only the magnitude changed for p-type materials. Ge and Si showing a decrease and PbS an increase.

806. Loyola University, New Orleans, La. **Electrical properties of single crystals of PbTe and PbSe.** Final Report, by P. B. PICKAR. 38 p., illus., 1957. (Contract Nonr-147301) (AD-218 452).

A study was made of the electrical properties of single crystals of PbTe and PbSe grown by the Bridgeman-Stockbarger method. Hall voltages and resistivity were measured as a function of magnetic field and temperature from 353°K to 77°K. Hall coefficients were calculated from Hall curves which were corrected for IR drop, as well as the Nernst and Ettingshausen effects. Most of the PbTe crystals grown were of the n-type. (TAB p. 6612, Dec. 15, 1959).

807. Loyola University, New Orleans, La. **Final report on contract.** Nonr 1573(01). Period 14 October 1956—15 July 1957, by P. B. PICKAR. 40 p., 1957. (PB 140 117).

A study was made of the electrical properties of single crystals of PbTe and PbSe grown by the Bridgman-Stockbarger method. Hall voltages and resistivity were measured as a function of magnetic field and temperature from 353°K to 77°K. Hall coefficients were calculated from Hall curves which had been corrected for IR drop, as well as the Nernst and Ettingshausen effects. Most of the PbTe crystals grown were of the n-type.

808. MACDONALD, D. K. C. and PEARSON, W. B. **Electron transport in copper and dilute alloys at low temperatures. I.** *Acta Met.* **3**: 392–408, figs., Jly. 1955.

The electric resistance of copper is noteworthy in showing a minimum at very low temperatures (> 10°K). This phenomenon has been traced to the presence of very small quantities of certain specific metallic solutes, and a corresponding remarkable variation of thermoelectric power has been observed in these dilute alloys. Detailed experimental studies of a wide range of alloys are presented in this and a companion paper, and the problems involved in preparing such very dilute alloys and interpreting the findings are discussed.

809. MACDONALD, D. K. C., PEARSON, W. B. and TEMPLETON, I. M. **Measurements of thermoelectricity below 1°K. I.** *Phil. Mag.* **3**: 657–660, June, 1958.

A few preliminary experiments in this temperature region on the noble metals, gold and silver are reported.

810. MACDONALD, D. K. C., PEARSON, W. B. and TEMPLETON, I. M. **Measurements of thermoelectricity below 1°K.** *Phil. Mag.* **4**: 380–383, figs., Mar. 1959.

Two earlier letters to the editor summarised some results of note obtained on the Group 1B and alkali metals in the temperature range below 1°K. Part III deals with some further results of interest on the heavier alkali metals and on various transition metals.

811. MACDONALD, D. K. C. and PEARSON, W. B. **Thermoelectricity at low temperatures. II. The alkali metal group.** *Roy. Soc. London. Proc.* **221A**: 534–540, 1954.

Thermoelectric behaviour of alkali metals (Na, K, Li, Rb, Cs) and some alloys at temperatures below 80°K.

812. MACDONALD, D. K. C., PEARSON, W. B. and TEMPLETON, I. M. **Measurements of thermoelectricity below 1°K. II.** *Phil. Mag.* **3**: 917–919, Aug. 1958.

Results of an initial survey of alkali metals.

813. MACDONALD, D. K. C. **Thermoelectric power in metals at low temperatures and anomalous impurity scattering.** *Physica.* **19**: 841–845, graphs, Sept. 1953.

Marked deviations from theoretical predictions were found by experiments with thermoelectric power of alkali metals from 90°K to liquid He temperatures.

814. MACDONALD, D. K. C. and PEARSON, W. B. **Thermoelectricity in metals at low temperatures.** *Acta Met.* **1**: 242–243, Mar. 1953.

Discusses experimental study of thermoelectricity on the alkali metals, Cu, Ag, and Au over a wide temperature range.

815. MACDONALD, D. K. C. and ROY, S. K. **Thermoelectric power of monovalent metals at high temperature.** *Phil. Mag.* **44**: 1364–1370, 1953.

The band theory of metals is applied to analyse the TE power of "simple" metals at high temperatures. The conventional analysis is first carried through for entirely free electrons and then extended to include variation in the number of free electrons per atom, departure from a quadratic dependence on energy on wave number, and non-spherical Fermi surface.

816. MACDONALD, D. K. C. and PEARSON, W. B. **Thermoelectricity at low temperatures. I. The "ideal" metals: sodium, potassium, copper.** *Roy. Soc. London Proc.* **219A**: 373–387, diags., 1953.

Following a short discussion of the present situation in the electron theory of metals with particular reference to thermoelectricity, experimental data on thermoelectricity at low temperatures is presented and discussed. The three elements—sodium, potassium and copper—have been chosen first as being frequently considered to be "quasi-ideal" metals. The influence of impurities has also been studied particularly in potassium-rubidium and dilute copper–tin alloys. It appears that the theory at present leaves much to be desired, but in any case considerable information on the fundamentals of electron scattering in metals can be obtained from these experimental studies.

817. MACDONALD, D. K. C. and PEARSON, W. B. **Thermoelectricity at low temperatures. II. The alkali metal group.** *Roy. Soc. London Proc.* **221A**: 534–540, figs., 1954.

In continuation of earlier work the thermoelectric behaviour of all the alkali metals, together with some alloys, has been studied, in the low temperature region below ~ 80°K. At best, only sodium conforms approximately with the predictions of conventional electron-transport theory; lithium and caesium in particular show positive thermoelectric powers over a whole range measured, and rubidium is also positive at the

lowest temperatures. A sharp inflexion is found in the thermo-emf of lithium at ~30°K. An empirical rule, useful in the discussion of dilute alloys, is proposed.

818. MacDonald, D. K. C. and Pearson, W. B. **Thermoelectricity at low temperatures. IV. Variation of thermoelectric power in a magnetic field.** *Roy. Soc. London Proc.* **241A**: 257–269, Aug. 7, 1957.

Experiments were made on the variation of thermoelectric power of pure sodium and copper and alloys of copper at low temperatures in a magnetic field. The variation in the pure metals is very small and in the case of sodium is qualitatively and quantitatively at variance with theory. The experiments on the alloys are well interpreted in terms of magnetoresistive behaviour and show that the anomalous scattering in copper + iron and copper + tin alloys is not affected significantly by a magnetic field.

819. MacDonald, D. K. C., Pearson, W. B. and Templeton, I. M. **Thermoelectricity at low temperatures. VII. Thermoelectricity of the alkali metals between 2° and 20°K.** *Roy. Soc. London. Proc.* **248A**: 107–118, figs., Oct. 28, 1958.

In earlier work, the absolute thermoelectric force E of the alkalis was measured from about 60°K down to about 4°K. The absolute thermoelectric power (S=de/dT) could then be derived with fair accuracy down to perhaps 8°K. The thermoelectric power of all the alkali metals has now been measured directly between 2° and 20°K, and the Thomson heats derived therefrom. The results are compared with the theory both of the "normal" thermoelectric power and the Gurevich or "phonon-drag" effect. It is clear from the work that experiments below 1°K in this field will be of much interest and a programme has been started in this temperature range.

820. Mansfield, R. **The electrical conductivity and thermoelectric power of magnesium oxide.** *Phys. Soc. Proc.* **66**: 612–614, Jly, 1, 1953.

Report of measurements on sintered specimens of MgO which indicate that it is a defect semiconductor.

821. Mansfield, R. and Williams, W. **The electrical properties of bismuth telluride.** *Phys. Soc. Proc.* **72**: 733–741, Nov. 1, 1958.

Measurements of the electrical conductivity. Hall coefficient, thermoelectric power and Nernst coefficient on specimens cut from zone-melted Bi_2Te_3 and on a single crystal are described.

822. Mansfield, R. and Salam, S. A. **Electrical properties of molybdenite.** *Phys. Soc. Proc.* **66B**: 377–385, May 1953.

The following electrical properties of natural crystals of MoS_2 were measured: conductivity, Hall coefficient and thermoelectric power over the temperature range −183° to 50°C. and the room-temperature change of conductivity in a magnetic field. It was found that the majority of the specimens were p-type semiconductors. The variation of the mobility of the charge carriers with temperature has been derived and indicates that the scattering of the charge carriers is mainly due to thermal vibrations of the lattice except at low temperatures when impurity scattering becomes important. Reasonable agreement is obtained between the values of the mobility calculated from the change in conductivity in a magnetic field, and from Hall coefficient and conductivity power measurements. The results of the thermoelectric power measurements and the variation of the concentration of charge carriers derived from the Hall coefficient are discussed and compared with theory.

823. Mansfield, R. **The electrical properties of bismuth oxide.** *Phys. Soc. Proc.* **62B**: 476–483, Aug. 1949.

The conductivity and thermoelectric power of Bi_2O_3 is measured over a temperature range of 680° to 150°C, and for variations of O pressures from 76 to 10^{-4} cm Hg. The thermoelectric power results can be summarised by the equation dE/dT 2 a + b/T, where a and b are constants, the positive sign of dE/dT indicating that Bi_2O_3 is a defect semiconductor. The results are discussed and good agreement is obtained between theory and experiment if it is assumed that normal Wagner and Schottky lattice defects become of importance at low temperatures when the concentration of free electrons is small.

824. Massachusetts Institute of Technology. Lincoln Laboratory, Cambridge, Mass. **Solid state research–Quarterly progress report.** 118 p., Oct. 15, 1959. (AFCRC-Tech Note 50–1018) (Contract AF19(604)–5200).

The thermoelectric power and electrical conductivity of praseodymium oxide, p. 23–25; Thermoelectric power of CdSb-ZnSb alloys (chart), p. 29.

825. Massachusetts Institute of Technology. Lincoln Laboratory, Cambridge. Mass. **Solid state research–Quarterly progress report.** 89 p., Jan. 15, 1960. (AFCRC Tech. Note 60–1000) (Contract AF19(604)–5200).

Thermoelectric power of praseodymium oxide, p. 17.

826. Massachusettes Institute of Technology. Research Laboratory of Electronics, Cambridge, Mass., and Laboratoire Central des Industries Electriques. **Investigation of physical properties of materials important in thermoelectric energy conversion.** Technical Final Report, Sept. 15, 1958 thru Sept. 15, 1959. 18 p., Sept. 1959. (Contract Nonr 1841(51).)

Principal goal of this investigation was a critical study of the various physical parameters involved in thermoelectric energy conversion.

827. Massachusetts Institute of Technology, Cambridge, Mass. **The formation of composite scales consisting of oxides of diffierent metals,** by

CARL WAGNER. 23 p., Aug. 31, 1955. (Rpt. 2) (Contract DA-19-020-ORD-224).

This is the second report for the Project titled Investigation to Measure the Thermoelectric Power of Certain Liquid Alloys.

The paper presents a theoretical analysis of diffusion processes during the oxidation of an alloy when oxides of different alloying elements are formed concurrently. For idealised conditions it is possible to calculate the decrease in the oxidation rate which results from alloying a base metal having a relatively high oxidation rate such as copper or iron with less noble metals such as aluminium, chromium, or beryllium whose oxides form relatively slowly.

828. Massachusetts Institute of Technology, Cambridge, Mass. **Investigation to measure the thermoelectric power of certain liquid alloys.** Final Report, September 1, 1952 to December, 31 1955, by CARL WAGNER. 4 p., 1955. (Contract DA-19-020-ORD-224).

Reviews work accomplished and technical reports prepared.

Investigations were continued under Contract DA-19-020-ORD-3661).

829. Massachusetts Institute of Technology, Cambridge, Mass. **The oxidation of alloys involving Noble metals,** by CARL WAGNER. 36 p., figs., Aug. 31, 1955. (Tech. Rpt. 1) (Contract DA-19-020-ORD-224).

This is the first report of the project titled Investigation to Measure the Thermoelectric Power of Certain Liquid Alloys.

Diffusion processes during the oxidation of alloys involving noble metals are analysed theoretically. An oxide film of uniform thickness is stable only if diffusion in the alloy is relatively rapid as compared with diffusion in the oxide of the less noble metal. Otherwise there is the tendency to form a rugged alloy–oxide interface. The oxidation rate is calculated for the limiting case of a scale consisting of protruding sections of the oxide of the less noble metal interspersed with slender trunks of alloy rich in the more noble metal. Under these conditions, the oxidation rate of alloys containing up to 50 percent of noble metal is supposed to be of the same order of magnitude as the oxidation rate of the less noble metal in its pure state.

830. Massachusetts Institute of Technology, Cambridge, Mass. **Thermoelectric power of liquid cadmium-antimony and zinc-antimony alloys,** by CARL WAGNER. 15 p., illus., Aug. 1955. (Tech. Rept. 3) (Contract DA-19-020-ORD-224).

Measurements of the thermoelectric power of liquid cadmium-antimony and zinc-antimony versus tungsten as reference metal have been conducted. Results rule out the possibility of semiconduction in these liquid alloys. Since CdSb and ZnSb are semiconductors, the structure of the solid compounds must differ substantially from the structure of the liquid phase.

831. Massachusetts Institute of Technology. Cambridge, Mass. **Quarterly progress report No. 52.** 186 p., Jan. 15, 1959. (Contract DA-36-039-sc-64637).

Thermoelectric processes and materials, p. 24–25. (Contract Nonr-1841(51)).

832. MCTAGGART. **The sulphides, selenides, and tellurides of titanium, zirconium, hafnium and thorium. III. Electrical properties.** *Australian J. Chem.* **11**: 471–480, Nov. 1958.

A study was made of the electrical characteristics of the primary compounds occurring in the binary systems of titanium, zirconium, hafnium and thorium with sulfur, selenium and tellurium. Properties investigated were resistivity, type of conduction (metallic n or p semiconduction), thermoelectric power and rectifying properties. A wide range of electrical characteristics was observed, reflecting the trend from semimetallic in the case of titanium to metallic in the case of thorium. The transition from non-metallic to metallic affinities that occurs from sulfur to tellurium is also evident. Data are presented tabularly.

833. MESNARD, G. and UZAN, R. **Conductivity and other electrical properties of thoria in vacuo.** Vide (Le) **6**: 1052–1062, Jly/Sept., and 1091–1097, Nov. 1951.

In French.

Details are given of experimental tubes used for the measurement of the resistance, thermoelectric emf and thermal conductivity of thoria. The purest available material was used; this was initially in the form of an amorphous powder, which crystallised on heat treatment. Results are presented and discussed in relation to possible mechanisms involved.

834. **Messungen ueber den thermoelektrischen homogeneffekt 3 grades (1. benedicks-effekt). (Measurements of the thermoelectric effect [of homogeneous conductors] of the 3rd power [of the temperature]. (1. Benedicks' effect).)** *Ann. Physik.* **16**: 210–226, Sept. 20, 1955.

In German.

Discusses measurements of platinum, gold and silver.

835. MIDDLETON, A. E. and SCANLON, W. W. **Measurement of the thermoelectric power of germanium at temperatures above 78°K.** *Phys. Rev.* **92**: 219–226, Oct. 15, 1953.

An experimental investigation on pure and impure Ge over the temperature range 78–925°K. At low temperatures, where conduction is due to impurity-introduced carriers, the sign of the thermoelectric power is the same as that of the Hall coefficient, the magnitudes of the thermoelectric power, resistivity and Hall coefficient increase with a decrease in the impurity content. With rising temperatures the magnitude of the thermoelectric power increases and passes through

a maximum, the value for p-type material subsequently passing through zero. The results are presented graphically.

836. MIKRIUKOV, V. E. and TIAPUNINA, N. A. **Investigation of the temperature dependence of the thermal conductivity, electrical conductivity and heat capacity of Bi, Pb and the Bi-Pb alloy systems.** *Fiz. Met. i Metalloved.* **3**: 31–41, 1956.

In Russian.

The measurement of thermal conductivity (HT) and electrical conductivity (ET) was carried out using Kohlraush's method. ET of pure Bi lies closer to that of semiconductors than to that of metals; in the temperature interval of −68 to +242°C, the temperature coefficient of ET is negative. The value of HT for Bi with a coarse-grained structure is greater than for a fine-grained strucutre, and in monocrystals it depends on the crystallographic direction considered.

837. MIKRIUKOV, V. E., TIAPUNINA, N. A. and CHERCHAKOV, V. P. **Thermal conductivity and electrical conductivity of bismuth-cadmium alloys.** *Moskov. Univ. Vest.* no. **1**: 127–136, 1956.

In Russian.

"Two systems weres tudied: Bi–Cd (I) and (Bi − 2% Pb)—Cd (II)."

838. MINDEN, H. T. **Effects of oxygen on lead sulfide films.** *J. Chem. Phys.* **23**: 1948–1955, 1955.

When outgassed, vacuum-evaporated PbS films are n-type semiconductors. If they are exposed to O at room temperatures, below about 200°, the conductivity decreases with increasing pressure and then increases again. The thermoelectric power changes from negative to positive, but less than 10^{-3} mole of O/mole of PbS is sorbed by the film. Above 200° the conductivity merely decreases when O is admitted, and the thermoelectric power becomes small. The film gradually absorbs all the O in the vacuum system and evolves a good deal of SO_2. When the reaction is complete, the conductivity returns to its initial value, and the thermoelectric power again becomes negative.

839. MINDEN, H. T. **Intermetallic semiconductors.** *Semiconductor Products.* **2**: 30–42, illus., Feb. 1959.

Includes a discussion of the preparation, properties and thermoelectric applications of bismuth telluride.

Article also appears in *Sylvania Tech.* Jan. 1958.

840. MIRGALOSVKAYA, M. S. and SKUDNOVA, E. V. **Investigations of alloys of the system AlSb Al_2-Te_3.** *Zhurn. Neorg. Khim.* **4**: 1113–1120, May, 1959.

In Russian.

"X-ray and microscopical analysis and measurement of the temperature-dependence of electrical conductivity (0–1100°C) showed that the AlSb-Al_2-Te_3 quasi-binary system is of eutectic type. The solid solubility of Al_2Te_3 in AlSb at ~ 800°C is ~ 45%. The structure of the solid solution is of ZnS-type, with a falling from 6·13 (AlSb) to ~ 5·99 A at Al_2Te_3 48%. The reverse potential increased from 3-5 V for AlSb to 18 V for Al_2Te_3 12·68%. The thermoemf/composition curve is given. Addition of a small quantity of Al_2Te_3 changes the conductivity from p- to n-type, but with **M**~ 20% it reverts to p-type again. (*Light Met. Bull.* **22**: 160, Feb. 17, 1960).

841. Missouri University. Department of Physics, Columbia, Mo. **Thermoelectric properties of porous semiconductors,** by E. B. HENSLEY. 24 p., Dec. 1, 1958. (Tech. Rept. 24) (Contract Nonr-2296(01)) (AD 215 081).

Properties of a class of porous semiconductors known as pore conductors are re-evaluated with regard to the possible application of these materials for thermoelectric power conversion. The theory of pore conductors is briefly reviewed. Calculations on the influence of space charge in these materials are extended. Estimates of the efficiencies of devices for thermoelectric power conversion utilising pore conducting materials are made. In general, the results appear very pessimistic as far as any prospect of high conversion efficiencies are concerned.

842. MIYATA, N. and FUNATOGAWA, Z. **Preliminary report on the magneto-thermoelectric power of nickel.** *Yokohama Natl. Univ. Sci. Rpt. I.* 13–18, Mar. 1954.

Not examined.

"This was measured by the same method as that used for iron. The results show positive signs and that (1) the magneto-thermoelectric power has a maximum at about −90°C and then decreases with decreasing temperatures and may tend to zero at 0°K, and (2) the magneto-thermoelectric powers between −90° and about 300° decrease with increasing temperatures but (3) in the neighbourhood of the Curie point they are negative signs and are produced by additive magnetisations which are proportional to the external magnetic fields, expected from the Weiss theory." *Sci. Abs.* **58A**: 6298, 1955.

843. MIYATA, NAHONORI and FUNATOGAWA, ENYA. **Magneto-thermoelectric powers of nickel single crystals.** *Phys. Soc. Japan. J.* **9**: 967–973, 1954.

Mathematical analysis of magneto-thermoelectric power of a single domain was developed for the case of many-domain nickel.

844. MIYATANI, S. **Electrical properties of Ag_2Se.** *Phys. Soc. Japan J.* **13**: 317, Mar. 1958.

Thermoelectric power can be measured as function of emf.

845. MIYATANI, S. **Electrical properties of Ag_2Te.** *Phys. Soc. Japan J.* **13**: 341–350, Apr. 1958.

The electronic conductivity, σ_e, Hall constant, R, and thermoelectric power, θ, in α Ag_2Te are measured as the Ag | Te ratio is varied by the use of the galvanic cell Ag | AgI | Ag_2Te | Pt, where the emf of the cell E represents the position of t ı :

Fermi level relative to Ag-saturated Ag_2Te. According as Ag is removed across the cell, starting from the Ag-saturated composition, σ_e decreases at first, and then increases. θ changes its sign at them inimum of σ_e, although R is always n-type, due to the large mobility ration ($\sim$ 100). The energy gap is, therefore as anarrow as several kT. When Ag is removed further, σ_e decreases again, keeping E constant. This is a mixed state of Ag_2Te and a new phase mentioned below. After a minimum of σ_e is attained, σ_e and E increase again, suggesting a new phase, AG $\sim$ 1·93 Te. The energy gap of this phase is larger than that in the Ag_2Te phase and the electron and hole mobilities are far smaller than those in Ag_2Te. When Ag is removed still further, σ_e and E become independent of the composition, indicating the precipitation of Te or Te-rich compound. These experimental data are compared with the Lorenz-Sommerfield theory, proving good accordance. Ionic conductivity is estimated.

846. MIYATA, SHIN-YA and YOKOTA, ISAAKI. **Galvano- and thermomagnetic effects in α-Ag_2Te.** *Phys. Soc. Japan J.* **14**: 750–754, June 1959.

Nernst coefficient, magnetoresistance, and magnetothermoelectric power along with conductivity, Hall coefficient and thermoelectric power of α-Ag_2Te are measured as functions of the emf, E of the galvanic cell Ag/AgI/ Ag_2Te/Pt.

847. MIYAZAWA, HISAO and SUGAIKE, SUEZO. **Phase transition in In_2Se_3.** *Phys. Soc. Japan J.* **12**: 312, 1957.

A phase transition occurs in single crystals at approximately 200°. At this temperature, the volume of the unit cell abruptly decreased, the electric resistance decreased by 2 orders of magnitude, the Hall coefficient increased by a factor of 6, and the thermoelectric power increased by a factor of approximately 3. On cooling these properties did not return until the sample was cooled below 100°.

848. MOKIEVSKY, L. I. and IVANOV, G. A. **Electrical properties of bismuth alloys. III. Iternary alloys: "Restoration" [in the alloys] of the properties of [unalloyed] bismuth.** *Zhurn. Tekh. Fiz.* **27**: 1695–1706, 1957.

In Russian.

In the four systems examined: Bi-Te-Sn, Bi-Te-P, Pb, Bi-Sn-Se, and Bi-Pb-Se, only the Bi-rich alloys were studied, the maximum total amount of the alloying addition being resp., 2, 5, 0·2 and 0·2-at-%. Thermo-emf of the alloys against Cu (t = 20°C, Δt = 50–60°C), Hall effect, and electrical resistivity were measured and the variation of the two latter properties in a changing magnetic field (3500–22,000 Oe.) was examined. The concentration and mobility of hole and electrons were calculated. The results (given in the form of graphs) confirmed the postulate that it should be possible to adjust the relative contents of the elements of Groups VI and VII in the investigated alloys in such a way as to "restore" to them the properties of unalloyed Bi. This is true for low concentrations under some conditions.

849. MONCH, G. C. **Thermo und voltaspannung des kupferoxydul. (Thermoelectric and constant potentials of cuprous oxide).** *Naturw.* **12**: 367, 1933.

In German.

A thermocouple has one element of Cu_2O and generates 0·4 to 0·5 volt at a temperature of 100 degrees centigrade.

850. MONCH, G. C. **Thermoelectricity of tellurium-metal couples.** *Ann. Physik.* **12**: 161–174, 1953.

Thermoelements were constructed by condensation of two metals in a high vacuum on thin celluloid film. Te (also Sb) was paired with Ag, Cu, Bi, and Sb. Effects were observed due to the diffusion of Ag into Te.

851. MOOSER, E., PEARSON, W. B. and TEMPLETON, I. M. **Thermoelectric measurements at low temperatures.** Programme of the Fall Meeting of the Electrochemical Society, Sept. 1958.

Abstract only.

"Thermoelectric measurements on compounds such as Bi_2Se_3, which are believed to contain intrinsic holes in the valence band and which should therefore have a relatively low resistivity even at very low temperatures, were reported and their possible use in thermoelectric cooling at temperatures lower than those normally considered were discussed." *Semiconductor Electron.* **2**: 2800, Nov. 1958.

852. MOOSER, E. and WOODS, S. B. **Thermoelectric power of germanium at low temperatures.** *Phys. Rev.* **97**: 1721–1722, Mar. 15, 1955.

Measurements of two samples at low temperatures provided evidence for an additional term Q_P in the thermoelectric power, arising from a "phonon-drag" effect, predicted by Gurevich.

853. MORGAN, F. H. and DANFORTH, W. E. **Thermocouples of the refractory metals.** *J. Appl. Phys.* **21**: 112–113, Feb. 1950.

The thermoelectric power of several refractory thermocouples was investigated, W–Ta for temperature measurements up to 3000°C, W–Mo up to 2600°C, Ta–Mo up to 2600°C, and W–W/Mo alloy (50% W/50% Mo) up to 2900°C. Basic calibration was carried out using several melting points and the results were verified and interpolated by means of an optical pyrometer. The couples W–Ta and W–Mo have been applied in this laboratory to the temperature measurement requirements in high temperature vacuum furnaces and determinations of spectral emisivity.

853. MORIGUCHI, Y. and KOGA, Y. **Electrical properties of GeTe.** *Phys. Soc. Japan J.* **12**: 100, Jan. 1957.

Curves of thermoelectric power Q, resistivity p and Hall coefficient R are given for polycrystalline and zone-melted single-crystal specimens over the range 100–700°K. The signs of Q and R are

positive and the temperature coefficient of p is positive throughout the temperature range. The carrier density is 10^{20}–10^{21} cm^{-3} for both types of specimen.

854. MORIN, F. J. **Electrical properties of α Fe_2O_3 and αFe_2O_3 containing titanium.** *Phys. Rev.* **83**: 1005–1010, Sept. 1, 1951.

Electrical conductivity, Hall effect and Seebeck effect have been measured on two sets of polycrystalline samples containing from 0·05 to 1·0 atomic % Ti (n-type impurity).

856. MORIN, F. J. **Electrical properties of α-Fe_2O_3.** *Phys. Rev.* **93**: 1195–1199, Mar. 15, 1954.

The conductivity, Seebeck effect and optical transmission of α-Fe_2O_3 have been analysed using two alternative models. The first model assumes conduction to occur in the d levels of Fe ions and yields a quantitative fit to the data. Mobility behaviour determined with this model is explained in terms of wavy bands. The second model assumes conduction in the sp bands of oxygen in addition to d-level conduction. It is shown qualitatively to be a reasonable model.

857. MORIN, F. J. and GEBALLE, T. H. **Electrical conductivity and Seebeck effect in $Ni_{0.80}Fe_{2.20}O_4$.** *Phys. Rev.* **99**: 467–468, Jly, 15, 1955.

These have been measured as functions of temperature on single crystal samples. A thermal hysteresis has been observed in the conductivity but not in the Seebeck effect. This suggests that the hysteresis involves the charge carrier transfer process but not the production of carriers. The activation energy associated with the transfer process is estimated to be 0·10 eV in the high-temperature state and 0·06 eV in the low-temperature state.

858. MULLARKEY, E. J. **Lead and its alloys [as chemical engineering materials of construction].** *Indus. Eng. Chem.* **51 (Pt. II)**: 1185–1189, Sept. 1959.

General developments, low temperature properties, thermoelectric applications, physical metallurgy, mechanical properties, nuclear uses, corrosion resistance, chemistry, etc.

859. MUSER, H. A. and SCHILLING, H. **Thermoelectric measurements on copper oxide at high temperatures.** *Z. Naturforsch.* **7a**: 211–212, Feb. 1952.

In German.

A note on experiments made to determine what types of semiconductor mechanism are possible in copper oxide at high temperatures.

860. MUSIKHIN, V. I. and ESIN, O. A. **A study of the properties of molten titanates by the emf method.** *Zhurn. Fiz. Khim.* **32**: 1372–1378, 1958.

In Russian.

"The electromotive force was measured for concentration cells without transport in Na_2O-TiO_2 and MnO–TiO_2 melts at 1200° and 1470°C. From the data obtained the activities of the components were calculated. The character of the electromotive force isoterms indicates a large negative deviation of these solutions from the ideal. Breaks in the curves were revealed corresponding to the congruent melting compounds Na_2O–TiO_2, Na_2O–$2TiO_2$, and 2MnO–TiO_2, bearing evidence of the ordering of the melts. As exemplified by the system Fe–Si, a comparison was made with the experimental data of the quasi-chemical formula. It was suggested that on melting the coordination number of FeSi decreases.

861. KAMADZIEV, P. R. **Electrical conductivity and thermal emf of white tin.** *Czechoslov. J. Phys.* **5**: 60–63, Feb. 1955.

In Russian with English abstract.

Electrical conductivity and thermoelectric power as a function of temperature was measured on samples of the grey modification of tin composed of fine white grains compressed in a suitable form during the transformation from the white to the grey modifications. The results of orientational measurements and their evaluation are reported.

862. KAMADZIEV, P. R. **Temperature dependence of thermo-emf of gray Sn with admixtures of Cd.** *Czechoslov. J. Phys.* **6**: 426–430, 1956.

In Czechoslovakian.

"The conductivity and thermo-emf of gray Sn containing $2{\cdot}8 \times 10^{18}$ atoms of Cd in 1 cc. were measured in the range from −183 to 10°C." *Met. Rev.* **31**: 48, Nov. 1958.

863. KAMADZIEV, P. R. **The temperature dependence of the thermal emf of gray tin alloyed with cadmium.** *Czechoslov. J. Phys.* **7**: 453–457, Oct. 1957.

In Czechoslovakian.

The thermal emf and electric conductivity as a function of the temperature in the range −183 to about 10°C was measured on samples of grey tin alloyed with cadmium. The specimens were prepared by alloying spectrally pure tin, which was then cooled in a closed container for a long period at −40° to −50°C so that during the *B* Sn→αSn transition a compression occurred of the individual grains. By analysing the results it was found that the activation energy increases with increasing concentration of cadmium and that cadmium behaves as a p-type impurity since specimens sufficiently alloyed with cadmium have a positive sign at lower temperatures, which becomes negative on entering the region of intrinsic conductivity when the influence of the electrons predominates. (*Sci. Abs.* **60A**: 4384, 1957).

864. KAMIGAICHI, T. **Electrical conductivity and thermoelectrical power of FeS_x (Pyrrhotite)** *Hiroshima Univ. J. Sci. Ser.* **A19**: 499–505, 1956.

Not examined.

"Polycrystalline specimens of FeS_x were prepared in which x ranged from 1·00 to 1·12. Electrical conductivity and thermoelectric power measurements were made at the same time by a

potential probe method in an atmosphere of CO_2 between room temperature and 400°. The results are consistent with the contraction of the lattice parameter c with increasing S concentration. *Chem. Abs.* **1**: 2384, 1957.

865. KANAI, Y. and NII, R. **Experimental studies on the thermal conductivity in semiconductors** *Phys. & Chem. Solids.* **8**: 338–339, 1959.

Report of International Conference on Semiconductors.

The thermal conductivity of Bi_2Te_3, PbTe, and InSb is reported, 100-600°K. No anomalous behaviour, such as reported by some investigators, was encountered.

866. KASATOCHKIN, V. I. and KAVEROV, A. T. **Electrical properties and structure of the transitional forms of carbon** *Akad. Nauk. SSSR. Dok.* **120**: 1007–1010, 1958.

In Russian.

The C samples used in testing were obtained by isothermal calcination of pyrolysis and cracking coal residues and of channel and thermal carbon blacks in N_2, the temperatures of up to 3200° being maintained for various times. The thermal emf was determined against Cu at constant temperature differences $\triangle T = 20°$. The resistance of powders was measured at pressures of 40 kg/.cm² The thermal emf α and the resistivity p of the samples heat-treated at 2000–2800° were presented graphically, as were also the changes of α and p with the heat-treatment temperatures.

Translation available from L.C. or S.L.A. (See *Tech. Trans.* **2**: 35, Jly. 3, 1959).

867. KATAOKA, S. and SUZUKI, T. **Conductive and thermoelectric properties of titanium dioxide semiconductors** *Electrotech. Lab. Bull. (Tokyo).* **18**: 732–741, 1954.

Not examined.

"Polycrystalline, semiconducting titanium oxide was prepared by reducing pure TiO_2 rods in purified H at various temperatures. The temperature dependence of the resistivity is expressed by the equation $p = p_0 \exp(\triangle E/2kT)$, and from this the activation energy is found to approximate 0·2 eV The thermoelectromotive force is generally larger than that of metals." *Semiconductor Abs.* **3**: 876, 1955.

868. KAUER, E., KLINGER, O. E. and RABENAU, A. **Ueber leitfachigkeitsmessungen im system ZrO_2–MgO. (Conductivity measurements in the system ZrO_2–MgO).** *Z. Electrochem.* **63**: 927–936, figs., Nov. 1959.

In German.

Thermoelectric power measurements showed positive charge carriers in all cases.

869. KELLY, F. M. and PEARSON, W. B. **The rubidium transition at ~ 180°K.** *Can. J. Phys.* **33**: 17–24, 1955.

Resistivity measurements showed a transition in Rb at about 180°K. The nature of this transition was investigated further by dilatometric and X-ray studies of thermal expansion, thermoelectric force measurements, and X-ray examination for the possibility of a change in crystal structure. Evidence of the transition in properties other than resistance measurements is very variable and although the transition does not appear to involve a change in crystal structure, its characterisation as an electronic change remains obscure. The resistive behaviour of Rb above 180°K is anomalous.

870. KETTEL, F. **Die waermeleitfaehigheit von germanium bei hohen temperaturen. (Heat conductivity of germanium at high temperatures).** *Phys. & Chem. Solids.* **10**: 52–58, Apr. 1958.

In German.

An account is given of thermal conductivity measurements on germanium monocrystals, both intrinsic and with high-hole conductivity. The author took mobility values, and values for the width of the forbidden zone and its dependence on temperature—all necessary for theoretical discussion of the electronic component of thermal conductivity—from the measurements of other authors, and confirmed them by comparison with his own measurements of thermoelectric force and electrical conductivity. The measured values of the electronic component of thermal conductivity, of both intrinsic and hole-conductive germanium, are about 4 times as high as those determined theoretically.

871. KIKOIN, A. K. and FEDOROV, G. D. **Semiconductive properties of magnesium bismuth alloys.** *Izvest. Akad. Nauk. SSSR. Ser. Fiz.* **20**: 1051–1508, 1956.

In Russian.

Since Group II–V compounds are expected theoretically to have highly ionic bonds, they should have good insulating properties. Mg and Bi were evaporated at a pressure of 10^{-6} mm on glass plates previously cleaned chemically and by ion bombardment. The relative amount deposited varied across the plate. The films were covered with a protective layer of SiO. The films were transparent for whit elight (to an extent of 20–5%) at places where their composition was Mg_3Bi_2. The same observation was made on films of Mg–As, Ca–Bi, and Ca–As. Electric conductivity was determined on plates which had previously vacuum deposited Cr or Mg contacts. The electric resistivity increases greatly near the Mg_3Bi_2 composition. Another maximum which increases considerably in air was observed at a 50-50 concentration. This second maximum decreases upon annealing at 250°. If both metals are evaporated separately, neither transparency nor high resistivity are observed unless the films are heated from 3 hours 230°. The temperature coefficient of conductivity shows semiconductor properties (hole conduction) in a large range of compositions around Mg_3Bi_2.

872. KIKOIN, A. K. and FEDOROV, G. D. **Thermoelectromotive forces in alloys of the system**

magnesium-bismuth. *Ural. Politekh. Inst. im. S.M. Kirova, Trudy.* **72**: 90–97, 1957.

In Russian. Not examined.

The "critical thickness" for the thermo-emf was 500 A for Bi and < 100 A for Mg. At the compound corresponding to Mg_2Bi_3, the thermo-emf showed a sharp maximum (> 1000 μv/°C). The positive sign of the thermo-emf showed that Mg_3Bi_2 is a hole-type semiconductor.

873. KLEMENS, P. G. **Thermoelectric power of univalent metals at high temperatures.** *Phil. Mag.* **45**: 881–882, 1954.

The Fermi energy of k is taken to be different from the value deduced from the free-electron model; the theoretical expressions for TE power can be made to agree well with experiment; and the values are no longer necessarily anomalous.

874. KMETKO. E. A. **Effect of ambients on the thermoelectric power and conductance of germanium particle aggregates.** *Phys. Rev.* **99**: 1642–1643, 1955.

Abstract only of paper given at meeting of American Physical Society, Toronto, Canada, June 1955.

The electrical and thermal resistances of aggregates of particles free of insulating surface films result almost entirely from the constriction of flow lines in the vicinity of the interparticle contact surfaces. In the case of germanium particles under small compressive loads the effective length of the constriction regions is comparable to the thickness of the space-charge layer. The thermoelectric power and dc conductance of such a system are, therefore, largely surface properties and an additional method is provided for investigating effects of various ambient atmospheres in shifting the bands at the surface.

875. KOC, STANISLAV. **Electromotive forces of thermoelements molybdenum–mercury, tantalum–mercury, and platinum–mercury at high temperatures.** *Czechoslov. J. Phys.* **4**: 250, 1954.

In Russian.

Thermal emf between Mo, Ta, or Pt, and Hg at 100-1500° followed the equation emf = AT^b, where emf is in mv., T in degrees. The constants A and b, respectively for various couples are: Mo–Hg $3{\cdot}750 \times 10^{-4}$, 1·649; Ta–Hg $1{\cdot}629 \times 10^{-4}$, 1,682; Pt–Hg $1{\cdot}795 \times 10^{-12}$, 4·194; in comparison, W–Hg $2{\cdot}006 \times 10^{-4}$, 1·723. At 1500° and higher, a normal electrical contact was not established. W-Cd thermocouple behaved analogously.

876. KOC, S. **Thermoelectric emf of W-Hg at high temperatures.** *Czechoslov. J. Phys.* **3**: 165, 1953.

In Russian.

Letter. The thermoelectric emf in millivolts is given as $2{\cdot}006 \times 10^{-4}T^{1{\cdot}723}$ where T is the temperature in degrees C within the range 100–150°C.

877. KOLOMIETS, B. T. and GORYUNOVA, N. A. **Properties and structure of ternary semiconducting systems. I. Electrical properties and structure of some materials in the system Tl-Sb-Se.** *Zhurn. Tekh. Fiz.* **25**: 984–994, 1955.

In Russian.

Alloys between Tl_2Se and Sb_2Se_3 were prepared by direct fusion and slow cooling. All were p-type semiconductors. Thermoelectric power, electrical conductivity, Hall effect and photoconductive spectral response were studied and evidence was obtained of the formation of a compound $Tl_2Se{\cdot}Sb_2Se_3$ (rhombic a = 4·15, b = 4·50, c = 12·0A). Preliminary work on alloys of Tl_2Se with As_2Se_3 and As_2Te_3 is reported. Amorphous glass-like materials were observed.

878. KOLOMOETS, N. V., NESHPOR, V. S. *et al.* **Thermoelectric properties of certain metal-like compounds.** *Zhurn. Tekh. Fiz.* **28**: 2382–2389, Nov. 1958.

In Russian. Tr. in Infosearch SEM–7–59.

Thermoelectric properties of some borides, carbides, nitrides and silicides are investigated. The borides and silicides are shown to behave similarly to typical metals.

879. KOLOMOETS, N. V. *et al.* **Thermoelectrical properties of some metal-like compounds.** *Soviet Phys. Tech. Phys.* **3**: 2186–2193, Nov. 1958.

Trans. of Zhurn. Tekh. Fiz. **28**: 2382–2389, Nov. 1958.

880. KOLOMOETS, N. V. **Thermoelectric properties of some compounds and alloys having a highly degenerate electron gas.** *Zhurn. Tekh. Fiz.* **28**: 936–939, May 1958.

In Russian. Translation in Infosearch Lit. Info. Serv. Russian Lit. Survey SEM–5–58, p. 6.1–6.6.

The semiconductor Institute of the Academy of Sciences of USSR has collected a number of data on the thermoelectric properties of carbides, nitrides and borides of the transition metals. The characteristic feature of these substances is their relatively low thermo-emf and the linear increase in resistance with temperature. This suggests the application of the theory of metals to these compounds and this application is discussed.

881. KOLOMOETS, N. V., STAVITZKAYA, T. S. and STIL'BANS, L. S. **Investigation of the thermoelectric properties of lead telluride and lead selenide!** *Zhurn. Tekh. Fiz.* **27**: 73–81, 1957.

In Russian. Translation in *Soviet Phys. Tech. Phys.* **2**: 59–66, 1957. Also in Infosearch. Tech. Lit. Info. Serv. Russian Lit. Survey SEM–2–57, 6.1–6.12, 1957.

Measurements were made of the temp. variation (100–700 K) of the thermal emf, electrical conductivity and carrier concentration for the whole range (0–100%) of solid solutions of the system PbTe–PbSe. From the measurements, temperature and composition variation of the carrier mobility and the effective cross-section(s) of scattering centres were derived. Complete results are given graphically. S never exceeded 2×10^{-18} cm².

882. MYERS, W. C. and BATE, R. T. **Thermoelectric properties of Bi_2Te_3-Bi_2Se_3 alloys.** *Am. Phys. Soc. Bull.* **4**: 409, Nov. 27, 1959.

Abstract of paper.

Electrical resistivity, thermoelectric power, and thermal conductivity were measured in the temperature range between 68°K and room temperature. The figure of merit was determined from the difference between adiabatic and isothermal resistivity measurement.

883. NASLEDOV, D. N. and SLOBODCHIKOV, S. V. **Study of the electrical and thermoelectrical properties of AlSb.** *Zhurn. Tekh. Fiz.* **28**: 715–724, Apr. 1958.

In Russian.

The following electrical properties of the semiconductor AlSb have been measured. Hall effect, specific conductivity, differential thermo-emf The results are discussed with reference to the various energy levels.

884. NASLEDOV, D. N. and FELTIN'SH, I. A. **The problem of electrical properties of gallium arsenoselenides.** *Soviet Phys. Solid State* **1**: 510–511, Apr. 1959.

Measurements of the differential thermal emf showed that in the region of the maximum electrical conductivity a slight decrease in the thermal emf takes place; then it increases and reaches a maximum when the composition is 3GaAs; Ga_2Se_3, after which it decreases and at 35 0/0 GaAs it changes its sign. This is in agreement with the fact that Ga_2Se_3 is p-type and GaAs n-type.

Translated from the Russian article in *Fiz. Tverdogo Tela* **1**: 565–567, Apr. 1959.

885. National Bureau of Standards, Washington D.C. **Properties of rutile. I. Electrical conductivity and thermoelectric power,** by H. P. R. FREDERIKSE and W. R. HOSLER. 48 p., Nov. 1, 1959. (Rept. 6585).

Describes and discusses measurements performed on TiO_2. Emphasis is on preparation of the specimens and their electrical properties (conductivity, Hall effect and thermoelectric power).

886. National Carbon Co., Cleveland, Ohio. **Thermoelectric materials,** by N. R. THIELKE. 3 issues Apr., June, Aug. 1959. (Bimon. Prog. Rept. 1, 2, 3) (Contract Nobs–77066) (AD–220–537); AD–229–057, AD–231–571).

Theoretical and experimental investigations are outlined to develop and evaluate materials for the conversion of heat to electric power by thermoelectric means. The materials include (1) graphites or other forms of carbon with usable thermoelectric characteristics, (2) refractory nitrides of group III elements including the lanthanide and actinide series, (3) solutions of alkali-metals in their fused halides, and (4) intermetallic compounds exhibiting the niccolite (NiAs), pyrite (FeS_2), and molybdenite (MoS_2) structures correlating properties with structure wherever possible and projecting this correlation to compounds with desired thermoelectric properties. Methods are to be developed for thermal conductivity measurements of small samples, including appropriate single crystals; the 700° to 1500°C range is of greatest interest. The formal thermodynamic approach to polycrystalline heterogeneous systems will be included, as well as research on the electron band structure of the new materials proposed for thermoelectric power generation. Small thermoelectric generators (0·1 w or larger) are to be constructed. (TAB p. 5558, Nov. 1, 1959).

887. **New thermoelectric materials.** *Mech. Eng.* **80**: 83, Oct. 1958.

Refers to Westinghouse announcement of new thermoelectric materials technically described as "mixed-valence compounds of the transition metals."

888. New York University, New York. **Research on Peltier effect cooling,** by E. MILLER, I. CADOFF *et al.* 18 p., Apr. 1956. (Quart. Prog. Rept. 1) (Contract DA36–039–sc–71133.)

The preparation and properties of alloys of the Pb–Te system are described. Factors affecting the efficiency of Peltier effect thermocouples are discussed.

889. New York University. College of Engineering, New York, N.Y. **Research on Peltier effect cooling,** by E. MILLER, I. CADOFF and M. TELKES. Final Report. 57 p., Aug. 1955.

A survey of pertinent literature is given and theoretical calculations are presented. Positive thermoelectric materials with ZnSb as the base were prepared and the effect of the addition of bismuth, tin and silver on the resistivity and thermoelectric power of the compound was determined. A similar investigation was carried out in alloys in which bismuth was substituted for antimony in ZnSb.

890. New York University. College of Engineering, New York, N.Y. **Thermoelectric properties of intermetallic compounds.** 8 issues, 1956, 1957, 1958. (Quart. Prog. Rept. 1 through 8.) (Contract AF33(616)–3883).

Purpose is to investigate the resistivity, thermoelectric power and mobility of carriers across the diagram of the lead-tellurium and the bismuth-tellurium systems, and in particular, to examine the nature of the fall-off of thermoelectric power on either side of the stoichiometric point.

891. New York University. College of Engineering, New York, N.Y. **Thermoelectric properties of intermetallic compounds.** 2 p., Dec. 1, 1958. (Quart. Prog. Rept. 9) (Contract AF–33(616) 3883.)

Work contract is being concentrated on determining the properties of the intermetallic compound BaTe. BaTe has been prepared successfully by direct reaction of barium and tellurium in a carbon crucible. Since the reaction is rather violent, this crucible is placed inside a steel bomb whose main function is to prevent scattering of the

reaction products. Preliminary electronic measurements on the samples indicated that the compound as prepared has a very large resistivity, in line with the estimated energy gap of several electron volts.

892. New York University. College of Engineering, New York, N.Y. **Thermoelectric properties of intermetallic compounds.** 2 p., June 1959. (Prog. Rept. 10) (Contract AF33(616)-3883) (AD-200-471).

Preliminary electronic measurements on the samples of the BaTe compound indicated this intermetallic compound has a high room-temperature resistivity; this fact is in line with the estimated energy gap of several electron volts. Circuitry was set up for the measurement of resistivity in the megohm range. The 2-point probe volt-ammeter method was used. The resistance was determined as a function of temperature by placing the specimen in a nichrome furnace inside a vycor tube through which N was passed to protect the specimen from oxidation. Room-temperature resistivities for several samples ranged between 10^{10} and 10^{6} ohm-cm but above 200°C, all samples showed resistivity vs temperature curves that indicated an activation energy of about 1 e.v. (TAB p. 5277, Oct. 15, 1959).

893. NIKITIN, E. N. **Elektroprovodnost' i termoelektrodvizhshchiia sila silitsidov perekhodnikh metallov. (Electric conductivity and thermoelectric power of the silicides of the transition metals).** *Zhurn. Tekh. Fiz.* **28**: 26–28, Jan. 1958.

In Russian.

Translation in *Soviet Phys. Tech. Phys.* **3**: 23–25, Jan. 1958. Also in Infosearch Tech. Lit. Info. Serv. Russian Lit. Survey SEM-5-58, p. 4.1-4.4.

With a view to their use in thermoelectric generators, the thermoelectric powers α, and electrical conductivities σ, of 23 silicides were measured. The method of specimen preparation is described; for each silicide two separate syntheses were made using Si of 00·000% and 99·03% purity. The results are tabulated; the effects of introducing impurities of Co, Ni and B into $MnSi_0$ and of B into $CrSi_2$ are described. Measurements of the thermal conductivities of $MnSi_2$ and $CrSi_2$ suggest that, with 800°C temperature difference between hot and cold junctions, the efficiency of thermoelectric generation should be ~5% for these two silicides.

894. NIKITIN, E. N. **Investigation of semiconductor properties in the silicon-manganese system.** *Soviet Phys. Solid State* **1**: 304–308, Feb. 1959.

Trans. of Russian article in *Fiz. Tverdogo Tela.* **1**: 340–343, 1959.

The measurement results for electroconductivity and the thermo-emf at room, high, and low temperatures gives reasons for the assumption that silicon and manganese form alloys with a metallic bond, and here, the best-regulated phases —silicides—are characterized by maximum values of electroconductivity and the thermo-emf.

895. NIKITIN, E. N. **Issledovanie temperaturnoi zavisimosti elektroprovodnosti i termoelektrodvizhushchei sily silitsidov. (Investigation of temperature dependence of electric conductivity and thermoelectromotive force of silicides.)** *Zhurn. Tekh. Fiz.* **28**: 23–25, Jan. 1958.

In Russian.

Translation in *Soviet Phys. Tech. Phys.* **3**: 20–22, Jan. 1958. Translation also in Infosearch Tech. Lit. Info. Serv. Russian Lit. Survey SEM-5-58, p. 3.1-3.3.

Manganese silicide, $MnSi_2$, and CoSi are characterized by a steady increase of electric conductivity with decrease in temperature. In the range from −200° to −800°C the values of electric conductivity change by a factor of only 2 to 3.

896. NIKOL'SKAYA, E. I. and REGEL, A. R. **Formation of solid solutions and the magnetic susceptibility in the systems HgTe-HgSe, HgTe-*B*MgS, HgSe-*B*HgS.** *Zhurn. Tekh. Fiz.* **25**: 1347–1351, 1955.

In Russian.

Magnetic susceptibility measurements given for the subject systems, both as alloyed and after annealing at 350°C. The measurements indicate a continuous series of solid solutions, verified by X-ray diffraction. αHgS transforms to βHgs in the presence of small amounts (less than 0·1%) of HgSe and HgTe.

897. NIKOL'SKAYA, E. I. and REGEL, A. R. **Some electrical characteristics of solid solutions HgTe-HgSe, HeTe-*B*HgS, and HgSe-*B*HgS.** *Zhurn. Tekh. Fiz.* **25**: 1352–1356, 1955.

In Russian.

Investigation of specific resistivity and its temperature coefficient, thermo-emf, and the Hall effects. Results, presented as graphs, show: electrical conductivity, Hall coefficient, thermo-emf, and electron mobility vs. composition; specific resistivity and Hall coefficient vs. magnetic field intensity. HgSe and HgTe prepared by heating the elements two hours at 800°C in an evacuated quartz tube; HgS, by heating at 400°C for 20 hours. Alternate method was heating the elements for 50 to 80 hours at 350°C in evacuated glass ampules. The first method gave large crystalline pieces, 3 mm. in diameter by 7 to 11 mm. long. Powders obtained by both methods were pressed into samples $28 \times 8 \times 2$ mm³. The electron mobility is 11,800 cm²/secV for pure HgTe and 14,200 cm²/Vsec for 40 HgTe–60 HgSe. Samples with over 30% HgSe had electronic conductivity; those under 30% HgSe had both electronic and hole conductivity. The changes of specific resistivity ($\triangle r/r_0$) and of Hall coefficient ($\triangle R/R_0$) of HgTe increase with increasing magnetic field strength. The other two systems are similar to HgTe-HgSe. Mobilities are high: HgSe-βHgS—10,000 cm²/Vsec and HgTe-βHgS—8,000 cm²/Vsec.

898. NISHIMURA, HIDEO. **Investigation of Pt-Mo alloys.** *Japan Inst. Metals. J.* **22**: 425–428, illus., 1958.

The electric resistance of Pt-rich alloys and the thermoelectromotive forces of Pt–(Pt–Mo) alloys were measured. The thermoelectromotive force shows a maximum value of about 3·5% Mo.

899. NISHIMURA, HIDEO. **Investigation of platinum-molybdenum alloys.** *Nippon Kinzoku Gakkai-Si* **22**: 425–428, 1958.

In Japanese. For English language entry, see Item 412, May 1959 issue.

900. NOGA, K. **Thermoelectromotive force of BaO and (Ba-Sr)O.** *Phys. Soc. Japan J.* **6**: 124–125, Mar./Apr. 1951.

Note. Generally observed as n-type although with poorly activated specimens, p-type conduction was found. Thermoelectric power values varied from 1·8 to 2·8 mV/°C in the range from 750° to 1200°C. Chemical potentials were calculated as from 1·8 to 2·6 eV, activation energies as 0·4 to 0·6 eV, and carrier concentrations as less than 10 in. cm^{-3}.

901. NORITOMI, KAZUO. **Investigation of thermoelectricity for metallic and silicate minerals.** *Tohoku Univ. Res. Inst. Sci. Repts. Ser.* 5, **7**: 94–101, 1955.

Thermal emf measurements on pyrite, galena, magnetite, quartz, and perthite from room temperature to about 600° are reported. Positive emfs (flow of electrons to the hot junction) were observed with quartz; this indicates positive-hole conduction, except in the lower temperature region. Irreversible changes occurred on heating above the α-β transition temperature. The other minerals exhibited negative emfs; this indicates electronic conduction.

902. North American Aviation, Inc., Downey, Calif. **The thermoelectric power of graphite; dependence on temperature, type, and neutron irradiation,** by W. P. EARTHERLY and N. S. RASOR. 28 p., 1952. (SR–196).

The thermoelectric power (q) of nine grades of artificial and natural graphite was measured in the temperature region 4·2–300°K. The effect of neutron exposure on the temperature dependence in this interval was determined also. An analytical expression for q was derived that it is in excellent qualitative agreement with the experimental data. Q is a reliable measure of the number of conduction electrons. The variation observed among grades of graphite is similar to the effect produced by slight changes in the number of conduction electrons. This variation in grade is correlated with particle size.

903. North American Aircraft, Canoga Park, Calif. **Thermal and electrical properties of graphite irradiated at temperatures from 100° to 425°K,** by G. E. DEEGAN. 77 p., Dec. 15, 1956. (Rept. SR–1716).

The pertinent results of a graphite cyclotron-irradiation programme are summarized. Experimental data are presented for the thermoelectric power, electrical resistivity and thermal conductivity of graphite (the medium-particle-size AWG type) as a function of several proton irradiations made at various temperatures.

904. NOVIKOVA, O. A. and RUDNITSKII, A. A. **Investigation of the system silver-platinum.** *Zhurn. Neorg. Khim.* **2**: 1840–1847, 1957.

In Russian.

"The hardness, electrical resistance (E), microstructure, phase structure and thermoelectric properties of alloys with 2·83–95% Ag were investigated.

905. NOVIKOVA, O. A. and RUDNITSKII, A. A. **Study of the system gold-silver-platinum.** *Zhurn. Neorg. Khim.* **3**: 729–749, 1958.

In Russian.

On a basis of thermal analysis and a study of the microstructure, hardness, short-time resistance to fracture, elongation, electrical resistance and its temperature coefficient and the absolute thermo-emf, a phase diagram of Ag–Au–Pt was constructed, and the properties of the phases in relation to composition and temperature were studied. The fusion of refined Pt, Au (impurities < 0·01%) and Ag reduced by glucose from AgCl was carried out in a VCh-furnace, in corundized crucibles. In the system Ag-Au-Pt, the presence of monovarient peritectic reactions was found, as a result of which a ternary solid α-solution, rich in Au and Ag, is formed. Isothermal sections at 900, 600 and 20° were studied. The absence of intermediate phases was confirmed. On constructing composition-property diagrams for sections parallel to the Au-Pt side, the Kurnakov principle of correlation is confirmed. On introducing Pt the unlimited solubility of Au in Ag becomes very limited. The addition of Ag to Au–Pt alloys constricts the region of the solid α-solution.

906. Nuclear Metals, Inc., Cambridge, Mass. **Electrical, thermoelectric, hardness and corrosion properties of vanadium-base alloys,** by H. J. Cleary. 34 p., Sept. 1956. (Rept. 1161). (Contract AT(30–1) 1565.

The thermo-emf of the alloys with Al, Cu, Mn, Ni, and Zr against Pt indicate that they are not suitable for thermocouples.

907. NYSTRON, JOSEF. **Thomson coefficients for copper at high temperatures.** *Ark. Matem. Astron. Fys.* **34A**: No. 27, 1947.

A comparison of absolute measurements with relative measurements by the thermoelectric effect.

908. OBROWSKI, W. **Thermoelemente. Edle thermopaare. (Thermoelements. Thermoelectric couples of precious metals.)** *Arch. Tech. Messen. No.* **264**: 13–14, 1958.

In German.

A study of the thermoelectric elements Pt, 10%, Ph/Pt, Pt 13%, Rh/Pt, Pt. 30%, Rh/Pt. 6%, Rh, Ir 60%, Rh/Ir, Pt. 5%, Rh/Au 46%, Pd 2% Pt.

Tables give the emf of elements for the range 0°–2000°C.

909. OFFERGELD, G. and VAN CAKENBERGHE, J. **Stoichiometry of bismuth telluride and related compounds.** *Nature* **184**: 185–186, Jly. 18, 1959.

Bismuth telluride, bismuth selenide and antimony telluride are being actively studied as semiconductors for thermoelectric cooling. By using a sensitive method of differential thermal analysis, it has been found possible to determine the composition corresponding to the maximum in the liquidus curve.

910. OLDEKOP, W. **Ueber thermoelektrische erscheinungen an glasern. (The thermoelectric phenomena in glass.)** *Glastech. Ber* **29**: 73–78, Mar. 1958.

In German.

Translation No. GB 105 available from Association of Special Libraries and Information Bureau, London.

Investigation relating to current theory on mechanism of conduction in silicate glass, according to which alkali ions diffused in glass are primarily responsible for current conduction. Results show that thermoelectric potentials of predicted order of magnitude are set up and that effect corresponds substantially with theoretical expectations.

911. ORNATSKAYA, Z. I. **The electrical nature of certain compounds of tungsten oxide.** *Zhurn. Tekh. Fiz.* **27**: 130–137, Jan. 1957.

In Russian.

In the first part experimental results are given by graphs for the temperature dependence of the electrical conductivity and the thermo-emf coefficient of sodium and lithium tungstate after heat treatment in the atmosphere and in a vacuum up to a temperature of about 550°C. In the second part these electrical properties are measured for the sodium tungstate and lithium tungstate bronzes. An exponential increase in the conductivity is found to occur from room temperature to some 260°C for specimens heated in the atmosphere. Also the conductivity is electronic, not ionic, and the sign of the thermo-emf coefficient is negative. The stability of the electrical properties is considered.

912. OTTER, F. A., Jr. **Thermoelectric power and electrical resistivity of dilute alloys of Mn, Pd, and Pt in Cu, Ag, and Au.** *J. Appl. Phys.* **27**: 197–200, Mar. 1956.

Data are given on the resistivities and thermoelectric powers of the alloys Cu-Pd, Ag–Pd, Au–Pd, Cu–Pt, Ag–Pt, Au–Pt, Cu–Mn, Ag–Mn and Au–Mn from −195°C to 500°C for the resistivities and to 650°C for the thermoelectric powers. The thermoelectric powers of the Pt and Pd alloys are negative relative to the pure solvents and are reasonably constant relative to the solvents at high temperatures. The thermoelectric powers of the Mn alloys become positive relative to the solvents above certain temperatures. A brief discussion of the data in relation to theory is given.

913. PARRAVANO, G. **Thermoelectric behavior of nickel oxide.** *J. Chem. Phys.* **23**: 5–10, Jan. 1955.

Measurements of the TE power of NiO containing Li_2O, CeO_2, Ag_2O, $NiCi_2$, Cr_2O_3, and WO_3. By use of an energy model proposed by Morin for NiO, the effect of the nature and concentration of additions on the Fermi level, hole concentration, and mobility were derived and discussed. For most of the samples, hole concentration can be related to chemical composition. Oxides containing electronic defects derived from d-electrons do not seem to have a typical conduction band. Rather, the conduction electrons migrate along localized levels. The formation of ion pairs for such a process depends on the energetic possibility of the lattice to deviate from the stoichiometric compn. The exchange of electrons within ion pairs is probably constrained by the presence of the large oxygen anion.

914. PARRAVANO, G. and DOMENCIALI, C. A. **Thermoelectric behavior of solid particulate systems. Nickel oxide.** *J. Chem. Phys.* **26**: 359–366, Feb. 1957.

Thermoelectric power measurements were performed on powdered NiO in the temperature range 60° to 220°C, under atmospheres of O_2, H_2, CO, CO_2, N_2O, He, and water vapor at different partial pressures.

915. PATRICK, LYLE and LAWSON, A. W. **Thermoelectric power of pure and doped silver bromide.** *J. Chem. Phys.* **22**: 1492–1495, 1954.

Measurements on single crystals of AgBr and AgBr containing 0·25% $CdBr_2$ in the range 455–667°K for AgBr and 381–539°K for AgBr–0·25% $CdBr_2$. Results interpreted in light of kinetic theories of Wirtz and S. R. de Groot. Results of Teltow on the ration of mobility of the interstitial Ag ions to that of the vacancies were consistent with the author's. No evidence of a contribution by Schottky defects to the thermoelectric power was found.

916. PEARSON, A. D. **Studies on the lower oxides of titanium.** *Phys. & Chem. Solids* **5**: 316–327, 1958.

Pure TiO is face-centred cubic above ~950°C. The structure of samples annealed below this temperature is complex, consisting of two or possibly three phases not in equilibrium. Impurities and excess of oxygen stabilize the face-centred cubic form at room temperature. The electrical resistivity of TiO (prepared by melting) is $2{\cdot}81 \times 10^{-4}$ Ω cm at room temperature between −162 and 362°C. The thermoelectric emf of TiO is of the same order of magnitude as that of metals. The measured density is less than the X-ray density, indicating that 14·6 per cent of the lattice positions are unoccupied. The properties of our products suggest that the TiO-phase oxides may be considered solid solutions of oxygen in titanium.

X-ray investigations indicate that Ti_3O_4 probably does not exist. The trigonal unit cell of Ti_2O_3 between room temperature and 350°C is confirmed. The lattice parameters change rapidly between 160° and 200°C, corresponding to the rapid increase in magnetic susceptibility. T-$_2O_3$ is antiferromagnetic; $\chi_M = 1{\cdot}09 \times 10^{-6}$ cgs units at 20°C. The thermal activation energy of electrical conduction of Ti_2O_3 in the room temperature region is about half of the observed optical activation energy. The material is a p-type semiconductor at room temperature.

917. Pearson, W. B. **Electron transport in copper and dilute alloys at low temperature. III. Solid solutions of iron in copper.** *Phil. Mag.* **46**: 911–919, Aug. 1955.

Systematic measurements of thermoelectric force and electrical resistivity of dilute alloys of iron in copper have been made at close intervals of temperature between 4·2 and ~ 50°K. These show that iron gives rise to particularly large anomalous thermoelectric effects and minima in the resistance when dissolved in copper.

918. Peri, G., Perrot, M. and Robert, J. **Thermoelectric effects shown by some oxides, investigation of cupric oxide.** *J. Phys. et Radium* **18**: 282–283, Apr. 1957.

This material of commercial grade in powder form was pressed between copper electrodes. The conductivity had a similar exponential dependence on temperature as other oxide semiconductors. For a temperature difference between the electrode the hot one became negative, unlike various other oxides studied.

919. Perrot, Marcel, Peri, Georges and Robert, J. **Experimental study on thermoelectric effects of certain oxide powders.** *Algiers Univ. Pub. Sci. Ser. B.* **3**: 107–120, Oct. 1957.

In French. Not examined.

"An investigation of the cells Al | Al_2O_3 | Al, Pb | PbO_2 | Pb, and Cu | CuO | Cu, wherein the oxide is in the form of a powder and one electrode is at an elevated temperature not exceeding 200°, while the other is at room temperature, indicates that they manifest thermoelectric power. The sign of the emf generated was negative when the cell was exposed to moisture and positive when dry." Bell Index Curr. Tech. Lit. J426 Nov. 15, 1958.

920. Perrot, Marcel, Peri, Georges, and Robert, J. **A thermoelectric effect with powdered metallic oxides.** *Conf. Uses of Solar Energy, Tucson*, 1955, Trans. **5**: 36–42, 1958.

A summary of experimental work on the properties of cells formed by two metallic plates compressing a powder therein an emf is generated is presented graphically for 3 cells with moist oxides: $Pb/PbO_2/Pb$; $Al/Al_2O_3/Al$; and $Cu/CuSO_4/Cu$. The sign and magnitude of the emf depended upon the type of oxide and the moisture content. The results are interpreted in terms of formation of concentration cells.

921. Perrot, Marcel and Peri, Georges. **Sur des elements thermoelectriques particuliers. (Particulate thermoelectric elements.)** *Acad. Sci. Paris. Compt. Rend.* **239**: 537–539, 1954.

In French.

When a powdered oxide of Al, Be, or Th is compressed between two metallic plates, a difference in temperature between the two plates results in an emf. When the oxide is moist, the positive pole is always the colder one, but if the oxide is dry, the positive pole is always the warmer one. However, with dry oxide the intensity of polarization is extremely weak, whereas with wet Al_2O_3 of 20 cm² surface, 1 mm. thick and 50 ohms resistance, compressed between two Al plates with a temperature difference of 220°C, a potential of 0·5V was generated and a current of 1 ma delivered for 3 hours through a resistance of 400 ohms. Considerable variation in the E and I produced with different samples of Al_2O_3.

922. Perrot, Marcel, Peri, G., Robert, J. and others. **Sur un effet thermoelectrique presente par de l'oxyde cuivrique en poudre. (A thermoelectric effect exhibited by cupric oxide in powder form.)** *Acad. Sci. Paris, Compt. Rend.* **242**: 2519–2522, May 23, 1956.

In French.

Experiments have been made with elements comprising powdered CuO compressed between two Cu electrodes. Graphs show the temperature variation of resistance of an element as a whole, and the variation of the thermo-emf as a function of the temperature difference between the electrodes for several elements; in one case the useful power is 22 mW/cm².

923. Pilat, I. M. **The electric and magnetic properties of the intermetallic compound cadmium antimonide.** *Fiz. Metal. i Metalloved.* **4**: 232–238, 1957.

In Russian.

The electrical resistivity, thermo-emf, Hall parameter, thermal conductivity and magnetic susceptibility were measured as functions of temperature for several specimens of CdSb. Specimens included stoichiometric, various small departures from stoichiometry, and various concentrations of Al, Te, Pb, Sn and In. Results are given in tables and graphs. The discussion related the measurements to the finding forces in the crystals.

924. Pilat, I. M., Iskra, V. D. and Shuman, V. B. **Electrical properties of the intermetallic compound CdSb with indium impurity.** *Soviet Phys. Solid State.* **1**: 354–357, Mar. 1959.

Trans. of Russian article in *Fiz. Tverdogo Tela.* **1**: 393–396, Mar. 1959.

The present paper reports studies of the temperature dependence of the electrical conductivity, the Hall effect, and the thermoelectric power of CdSb samples with indium impurity.

925. PILAT, I. M. **Electric properties of the intermetallic compounds CdSb.** *Zhurn. Tekh. Fiz.* **27**: 119–122, 1957.

In Russian.

Electric conductivity and thermal emf from −180 to + 250°C., the rectification of CdSb at the point contact and the triode effect.

926. PILAT, I. M., CHIZH, L. D. and VOITYSHEN, S. U. **Elektrisheskii i magnitnie svoistva sisteme ZnSb-CdSb. (Electrical and magnetic properties for the system ZnSb-CdSb).** *Zhurn. Tekh. Fiz.* **28**: 786–788, Apr. 1958.

In Russian.

Electrical conductivity, thermo-emf and Hall effect of this semiconductor have been measured.

927. PIMENTEL, G. C., and SHELINE, R. K. **The Fermi gas model applied to the thermal electromotive forces of tin, lead and indium.** *J. Chem. Phys.* **17**: 644–647, Jly. 1949.

The absolute thermoelectric powers of Sn, Pb, and In in the range of 2–10°K are taken from data of Keeson and Matthijs. The temperature dependence of thermal emf is parabolic, as predicted for a Fermi gas. With an additional assumption regarding a mean free path parameter, the Fermi energies for Sn, Pb, and In are calculated to be 5·72, 2·89 and 1·20 eV, respectively. Low temperature specific heat data then provide an estimate of the number of conduction electrons per atom. The latter values are 2·54, 2·39, and 0·50 respectively.

928. PINNICK, H. T. **Hall constants and thermoelectric power of titanium alloys.** *Am. Phys. Soc. Bull.* ser. 2, **3**: 254, June 19, 1958.

Abstract only.

The change in electrical resistivity of titanium when alloyed with silver, aluminium, and tin has been shown to be essentially independent of the valence of the solute. In an effort to study changes of electron concentration in these same alloy systems, their Hall constants and thermoelectric power have been measured. Qualitatively, the Hall constants and thermoelectric powers of the three alloy systems are quite similar. However, in contrast to the case of electrical resistivity, there is a definite dependence on solute valence. The initial slope of Hall constant as a function of concentration for the silver alloys is greater by a factor of two than for the tin alloys, while the initial slopes of thermoelectric power at 80°K as a function of concentration for these two alloy systems have different signs.

929. Pittsburgh University, Pittsburgh, Pa. **Rare earth chalcogenides,** by A. R. FREDA. 2 p., Nov. 30, 1959 (Tech. Prog. Rept. 1) (Contract NOba-77068) (AD 231572).

Studies were undertaken to develop and prepare a thermoelectric power generating material from the rare earth compounds of one or more of the lanthanide series of elements with group VI B elements. Resistivity measurements were made on the commercially pure rare earth oxides and the high-purity ceric oxide produced from an iron exchange process before and after sintering. The measurements were also made on the doped and undoped compacts.

930. PIWKOWSKI, T. R. **Some semiconductive properties of dilute binary solid solutions of bismuth in tellurium and tellurium in bismuth.** *Nature*, **184**: 355–356, Aug. 1, 1959.

The thermoelectric power, type of conductivity, conductivity and magnitude of the photoconductive properties of dilute binary solutions of Bi–Te are given. It is suggested that these solid solutions are semiconductors.

931. PLESSNER, K. W. **Conductivity, Hall effect and thermoelectric power of selenium single crystals.** *Phys. Soc. Proc.* **64B**: 671–681, Aug. 1, 1951.

Conductivity obeys the law $\sigma - \sigma_0 \exp(-eE/kt)$ with $eE = 0{\cdot}13$ eV Ohm's law is not obeyed for applied fields > 5V/cm. Both thermoelectric power and Hall effect rise slightly with increasing temperature, indicating a decreasing concentration of current carriers (positive holes). The evidence points to the existence of intergranular barriers in single crystals.

Condensed version of this article appears in *Nature*, **165**: 970–971, June 17, 1950.

932. POKATILOV, E. P. **Consideration of transferred charges in the theory of thermoelectric phenomena.** *Uchenye Zapiski Kishinev. Univ.* **24**: 115–126, 1956.

In Russian.

A correction involving the consideration of electric charges transferred in the process of diffusion is introduced in the derivation of the relation between the coefficient of the thermo-emf α and the temperatures. Cases are considered of a semimetal at low temperatures, a semimetal and a semiconductor at high concentrations of the current carriers, and of a semimetal with a low concentration of the latter.

933. POLLOCK, D. D. and FINCH, D. I. **Effects of alloying elements on the electrical properties of manganin-type alloys.** *J. Metals.* **8**: 203–210, 1956.

Relationships between the compositions of specially prepared manganin-type alloys and some of their electrical properties have been established. Empirical equations, based upon the electronic configurations of the alloying elements, are given which describe the resistivity, temperature coefficient, peak temperature, and thermoelectric power of Cu–Mn–Ni–Fe alloys at approximately room temperature. Calculations based upon these relationships are correlated with experimental data.

934. POLLOCK, D. D. and FINCH, D. I. **Electrical properties of Cu-Mn-Al-In-Fe and Cu-Mn-Al-In-Fe-Ni alloys.** *AIME Met. Soc. Trans.* **212**: 841–846 Dec. 1958.

Empirical relationships between the composition and some of the electrical properties are estab-

lished. Equations, based upon the electronic configurations of the alloying elements, describe the resistivity, temperature coefficient, and thermoelectric power of these alloys in the neighbourhood of room temperature.

935. POLLOCK, D. D. and FINCH, D. I. **Electrical properties of Cu-Mn-Al-In-Fe and Cu-Mn-Al-In-Ni-Fe alloys.** *Am. Inst. Mining Engrs. Met. Soc. Trans.* **212**: 841–846, Dec. 1958.

Resistivity, temperature coefficient and thermoelectric power at room temperature depends on composition. (*Met. Lit. Rev.* **15**: 693, 1958).

936. POTTER, R. D. **Calibration of a nickel-molybdenum thermocouple.** *J. Appl. Phys.* **25**: 1383–1384, Nov. 1954.

Values of emf were determined up to 2242°F.

937. POWELL, HANDELL and EVANS, E. J. **The Hall effect and some other physical constants of alloys. The aluminium-silver series of alloys.** *Phil. Mag.* **34**: 145–161, 1943.

The thermoelectric power with respect to copper of an alloy of aluminium and silver varies with its composition between + 1 and −4 microvolts per degree centigrade.

938. POWELL, R. L., RODER, H. M. and HALL, W. J. **Low-temperature transport properties of copper and its dilute alloys, pure copper annealed and cold drawn.** *Phys. Rev.* **115**: 314–323, Jly. 15, 1959.

Experimental results for thermal conductivity, electrical resistivity and thermo-electric force and power between 4° and 300°K.

939. POWELL, R. L., HALL, W. J. and RODER, H. M. **Low-temperature transport properties of commercial metals and alloys. II. Aluminiums.** *J. Appl. Phys.* **31**: 486–503, Mar. 1960.

Thermal conductivity, electrical resistivity, Lorenz number, thermoelectric force, and thermoelectric power are given in the temperature range 4–120°K for ten aluminiums and aluminium alloys. The thermoelectric power of some of the alloys is positive with respect to high purity sample, for others it is negative. The various properties, methods of analysis, and separation of components are discussed in detail.

940. PRESNOV, V. A. and SYNOROV, V. F. **Preparation and investigation of intermetallic compounds in the form of thin layers.** *Zhurn. Tekh. Fiz.* **27**: 123–126, Jan. 1957.

In Russian.

"Thin specimens were prepared of the following $A^{III}B^{V}$-type compounds: AlSb, InSb, GaSb, as well as of various pure group IV elements. The specimens were prepared as follows: thin layers each 0·1–1 μ thick were evaporated on top of each other to produce strip specimens with thickness varying (in a direction parallel to the width) from one layer to about fourteen layers. Measurements of the electrical resistivity p parallel to the length and the thermal emf (α) gave the following results: (1) p for pure group IV semiconductors varied little with thickness (t) and was close to the bulk value; α was very small and difficult to measure. (2) p for $A^{III}B^{V}$ films varied greatly with t, having a sharp maximum at 2-3 layers thick; the largest p measured was about 30 ohm cm. (3) The variation of α with t for $A^{III}B^{V}$ films was similar to the variation of p. The maximum α measured was 220μV/°C. (4) The Hall parameter was measured on suitable specimens and was always >0. The variations of α and p with t are ascribed to variation of composition. Maxima correspond to stoichiometric $A^{III}B^{V}$ but the values at maxima differ greatly from bulk values for the same compounds."

941. **Progress made in semiconductors.** *Chem. & Eng. News.* **37**: 34, Sept. 14, 1959.

A Boston technical session revealed advances such as cobalt silicide in thermoelectric generators; improved GeTe materials which boost thermoelectric generator efficiencies in the 700° to 950°K. range; and new alloying systems such as indium arsenide-gallium arsenide which show promise in thermoelectric power generators operating with hot junction temperatures between 500° and 700°C.

942. PROPOPOPESCU, M., CRIMER, D., FOKT, E. and DULAMITA, T. **Semiconductor properties of antimony-zinc alloys.** *Acad. Rep. Populare Romine, Studii Cercetari Met.* **4**: 33–57, 1959.

In Roumanian. Not examined.

"The variations of the electrical and thermoelectrical properties of Sb–Zn alloys are investigated as functions of their composition and structure. The alloys are produced in vacuo or under Ar. Zn, purified to 99·92, and Sb, purified to 99·86 and 99·9998%, are used. The electrical resistance, as a function of the composition and the structure of the alloys, shows a pronounced maximum in the case of SbZn at p = 14,320 μΩcm. With 30-45% Zn the semiconductor character of the alloys is especially notable. In a number of these alloys the activation energy for the thermal transitions of the charge carriers $\triangle\varepsilon$ is calculated to be 0·46 eV. The relation between the thermo-emf (α) and the electrical conductivity (σ) is $\alpha = 456{\cdot}5 - 81{\cdot}4 \log \alpha$ in the entire range of the alloy system Sb–Zn." *Chem. Abs.* **53**: 14707, 1959.

943. PTUSHINSKII, YU. G. and LUPAN, YU A. **Sign of conductivity of powdered germanium films.** *Ukrain. Fiz. Zhurn.* **4**: 125, 1959.

In Ukrainian.

"The electrical conductivity of Ge films obtained by sublimation of Ge was investigated. During sublimation a vacuum of 5×10^{-9} mm Hg was maintained. The film has electrical conductivity. The sign of the conductivity was determined by the thermo-emf sign and its absolute value was found to be in the order of 1 mV/degree. Ge films obtained in 10^{-5} mm vacuum showed hole-type conductivity which is not inherent to the film but is probably due to the effect of remaining gas molecules." *Chem. Abs.* **53**: 17678, 1959.

944. PULLAN, G. T. **The thermoelectric behaviour of tin and silver at liquid-helium temperatures.** *Roy. Soc. London. Proc.* **217A**: 280–293, figs., 1953.

A new method, employing a superconducting galvanometer and requiring a temperature difference of only 0·01°K between the ends of the specimen, has been used to measure the absolute thermoelectric powers of tin and silver. The thermoelectric behaviour of metals in the normal (non-superconducting) stage shows striking disagreement with the predictions of the free-electron theory. Thus, the thermoelectric power does not vary linearly with the absolute temperature, and for silver has a positive, instead of a negative, sign. The thermoelectric power is profoundly influenced by the presence of strains in the specimens, and by very small amounts of impurity, the temperature dependence becoming more nearly linear for impure or highly strained specimens. A marked anisotropy has been found in the thermoelectric behaviour of single crystals of tin.

945. Purdue Research Foundation, Lafayette, Ind. **Semiconductor research.** 32 p., 1957. (Quart. Rept. 4) (Contract DA 36-039-sc-63222) (AD-140 582).

A progress report on several projects in semiconductor research. Included in the discussion is the thermoelectric power of InSb at high temperatures.

946. Purdue University. Physics Department, Lafayette, Ind. **Semiconductors at low temperatures,** by V. A. JOHNSON and K. LARK-HOROVITZ. 59 p., 1956. (Special Rpt.) (Contract DA36-039-sc-71131).

Measurements made in the liquid hydrogen and liquid helium temperature ranges are useful in obtaining information about the basic nature of semiconductors. The investigations considered are of resonance phenomena, electrical properties, including resistivity, magnetoresistance, Hall coefficient, and thermoelectric power, thermal properties such as specific heat and thermal conductivity, and optical properties such as absorption and photoconductivity.

947. PUTLEY, E. H. **The Hall coefficient, electrical conductivity and magnetoresistance effect of lead sulphide, selenide and telluride.** *Phys. Soc. Proc.* **68B**: 22–34, Jan. 1955.

The experimental procedure and results are described for measurements of the Hall coefficient and electrical conductivity of single crystals and natural specimens of PbS, PbSe and PbTe over the temperature range 77–1000°K. Some measurements at 20°K are also described. The magnetoresistance effect was also measured on some specimens at a number of temperatures between 20°K and 300°K. At high temperatures all specimens show intrinsic behaviour. This will be discussed in detail in a subsequent paper but the behaviour in the extrinsic range, the temperature dependence of the mobility and irreversible effects found at high temperatures are discussed. It is concluded that the general behaviour of the effects considered can be accounted for by the usual semiconductor model.

948. PUTLEY, E. H. **Thermoelectric and galvanomagnetic effects in lead selenide and telluride.** *Phys. Soc. Proc.* **68B**: 35–42, 1955.

Describes measurements of TE power and the Peltier, Nernst, Ettingshausen, and Righi–Leduc effects; behaviour is in accordance with conventional semiconductor theory. The coefficients are also calculated from the known value of the Hall coefficient and conductivity. Good agreement obtained between measured and calculated galvanomagnetic coefficients. From observation of the Peltier effect, an estimate of the thermal conductivity is obtained. Comparison of measured and calculated values of TE power permits establishment of the effective mass of carriers in PbSe, about 0·3 m. The thermal conductivity can be established from the Peltier temperature difference set up when a current is passed through the crystal. Values obtained for the Ettingshausen coefficient show that errors in d.c. Hall effect measurements due to this effect should not be greater than 1%, which is not large compared with other errors likely to be present.

949. Radio Corporation of America, David Sarnoff Research Centre, Princeton, N.J. **Thermal and electrical properties of material.** 10 p., June 30, 1959. (Prog. Rept. 2) (Contract AF33 (616)-6165).

High-temperature measurements of thermoelectric power and resistivity are described for the In_5Ga_1 alloy. Preliminary diffusivity results in an n-type sample of germanium from room temperature to 750°C are given.

950. Radio Corporation of America. David Sarnoff Research Centre, Princeton, N.J. **Thermal and electrical properties of material.** 9 p., Sept. 30, 1959. (Prog. Rept. 3) (Contract AF33 (616)-6165).

Measurements of thermoelectric power and resistivity as a function of temperature have been made on an alloy $In_{0.8}Ga_{0.2}As$.

Preliminary analysis on the diffusivity measurements on germanium has been made. This analysis indicates a considerable anharmonic contribution to the specific heat.

951. RAUSCH, K. **Investigations of antimony single crystals in a transverse magnetic field. (Electric and thermal resistance; thermal emf).** *Ann. Physik.* **1**: 190–206, 1947.

In German.

Single crystals of Sb and two constantan-manganin thermocouples were investigated in an apparatus described by Grüneisen and others.

952. **Rae materials for electronic and new ceramics.** *Ceram. Indus.* **74**: 90–101, Jan. 1960.

Names of materials are alphabetically listed,

and under these are given properties and uses. Several thermoelectric materials are included.

953. REIMER, LUDWIG. **The thermoelectric force of thin evaporation layers.** *Z. Naturforsch.* **12a**: 525–526, 1957.

Evaporation of both layers (Cu and the tested metal) took place in vacuo. (1 to 2 × 10^{-5} mm.) with an evaporation velocity of 100A/sec. through displacement of diaphragms in a high vacuum so that the layers were not exposed to air. Measurement of thermo-emf done by a compensations switch. The measurement extends to a 50A thickness of Bi, at which point a change of sign in the thermo-emf is observed. This is observed in Ni layers thinner than 40A; in Ni, thermo-emf begins to decrease at 400–500A., in the order of magnitude of the average free path of the conducting electrons. The relation between layer thickness and thermo-emf is shown for Te, Sb, Bi, Fe, Cu, Ni, Co, and Al.

954. Research Chemicals, Burbank, Calif. **Refractory gadolinium and hafnium compounds.** May 18 to Dec. 31, 1959. ¼ in. thick. Dec. 31, 1959. (RC-134) (Contract NObs-77145).

Gives data obtained so far during investigations of the Seebeck coefficients and resistivities of gadolinium and hafnium.

955. REZANOV, A. I. **Thermal and thermoelectric properties of ferromagnetic metals.** *Akad. Nauk. SSSR. Dok.* **82**: 885–887, 1952.

In Russian.

By the procedure of Vonsovskii on calculating the electrical conductivity of ferromagnetic metals from the interaction between the 3d electrons of the atoms and the 4th electrons in the crystal lattice, an analogous formula is obtained for the coefficient of heat concentration. The temperature dependence of the ferromagnetic contribution to the magnitudes is determined mainly by the square of the spontaneous magnetisation, and, consequently, the temperature coefficients must have a sharp maximum near the Curie point.

956. RICHARDS, WALLACE and EVANS, E. J. **The Hall effect and other physical properties of the copper-cadmium series of alloys.** *Phil. Mag.* **13**: 201–225, 1932.

The thermoelectric power with respect to lead of a copper-cadmium alloy varies with its composition −4 and + 21 microvolts per degree centigrade.

957. RIETZSCH, A. **Ueber die thermische und elekrische leitfahigkeit von kupfer-phosphor und kupfer-arsen. (On the thermal and electrical conductivity of CuP and CuAs).** *Ann. Physik.* **3**: 403–427, 1900.

In German.

958. ROBERTSON, W. D. and UHLIG, H. H. **Electrical properties of the intermetallic compounds Mg_2Sn and Mg_2Pb.** *Metals Tech.* **15**: *Tech. Pub.* 2468, p. 1–11, tables, Oct. 1948.

Thermoelectric measurements show that the conduction mechanism is predominantly electronic. The thermoelectric power of Mg_2Sn is negative relative to copper and is equal to 90 microvolts per degree in the range of 15° to 100°C. The compound, therefore, analogous to ZnO, is an excess type semiconductor. The thermoelectric potential is a power function of temperature over the range of 20 to 460°C. the experimental values of which may be approximated by a relation of the form: Em.v. = $-32{\cdot}55 + 13{\cdot}06 \times 10^{-2}T - 6{\cdot}7 \times 10^{-5}T^2$ where T is the absolute temperature.

959. RODER, H. M., POWELL, R. L. and HALL, W. J. **Thermal and electrical conductivity of pure copper.** *In* International Conference on Low Temperature Physics and Chemistry. Proceedings. 5th, 1957, p. 364–367, figs., Madison University of Wisconsin, 1958.

Measurements of the thermal and electrical conductivity and thermal emf for three related coppers in the temperature range 4 to 120°K.

960. RODOT, MICHEL. **Properties of the semiconductor Insb.** *J. Phys. et. Radium.* **19**: 140–150, Feb. 1958.

In French.

The properties of the semiconductor InSb are reviewed. Special attention is paid to the uncertainty prevailing about the important features: the exact value of the electron effective mass and the mechanism of scattering of the electrons. The theory of the thermoelectric and thermomagnetic effects in InSb is then given and experimental results are presented which support the idea that scattering by the optical lattice vibration is the predominant mechanism.

961. RODOT, MICHEL. **Theorie de l'effet magneto-thermoelectrique transversal dans les semiconducteurs. (Theory of the transverse magneto-thermoelectric effect in semiconductors).** *Acad. Sci. Paris. Compt. Rend.* **243**: 129–132, Jly, 9, 1956.

In French.

The laws governing the variation of the Seebeck effect in the presence of a transverse magnetic field are established, starting from Boltzmann's transport equation and assuming dispersion of charge carriers by ionisation impurities.

962. RODOT, MICHEL. **The properties of indium antimonide.** *J. Phys. et Radium.* **19**: 6s, 1958.

In French.

A Note. There are two controversial questions: the effective electron mass and the mechanism of electron scattering. The variation in thermoelectric effect by a transverse magnetic field was studied; the results indicated that scattering is due to optimum vibrations of the lattice.

963. ROMANKEVICH, V. N. and SIDYAKIN, V. G. **Electrical properties of amorphous selenium with iodine impurity.** *Izvest. Vysshi'h Ucheb. Zaved. Fiz.* **6**: 25–32, 1958.

Thermoelectric power a was also measured for

pure amorphous selenium it was equal to 1·1 mV/deg. The temperature dependence of the thermoelectric power a was obtained for samples of amorphous selenium with iodine. The sign of the thermoelectric power indicated that pure selenium and selenium with iodine have hole conductivity. (*Selenium and Tellurium Abs.* **1**: 22, 1959).

964. Rosi, F. D., Abeles, B., and Jensen, R. V. **Materials for thermoelectric refrigeration.** *Phys. & Chem. Solids.* **10**: 191–200, Jly. 1959.

The electrical conductivity, thermoelectric power and thermal conductivity were measured on various materials. Criteria determining the optimum properties of the materials for thermoelectric refrigeration are discussed.

965. Ross, I. M. and Saker, S. W. **Applications of InSb.** *J. Electron.* **1**: 223–230, 1955.

InSb can be used: (1) for detection of long-wave radiation (to 7·5μ when cooled to 77°K), photomagnetic, photovoltaic, and photoconductive properties can be used; (2) as an infrared filter material; (3) as a thermoelectric generator material although not very efficient, owing to high thermal conductivity (factor of merit 10×10^{-3} as compared to 31×10^{-3} for Bi_2Te_3); (4) for measurements of electric fields by the Hall effect, or use as a compass; (5) as a Hall effect wattmeter and for other metering applications; (6) as a Hall effect amplifier, when inserted into a nearly closed magnetic core; and (7) as a resistance gyrator and in several other applications based on magnetoelectric properties.

966. Rudnitskii, A. A. **Investigation of the electric and thermoelectric properties of alloys of platinum with copper.** *Sektora Fiz-Khim. Anal. Inst. Obshchei Neorg. Khim. Akad. Nauk. SSSR, Izvest.* **27**: 171–184, 1956.

In Russian.

"In the concentration interval from 0 to 100%, an investigation was made of the electric and thermoelectric characteristics of a Cu-Pt alloy in hardened and annealed states. The resistance was measured at 25° and 100°, the absolute thermal emf was studied in the temperature range from room temperature to 1000°. The concentration dependence of the electric resistivity and its temperature coefficient for hardened alloys has a shape that is characteristic of a continuous series of solid solutions . . . It is concluded that when a solid solution is cooled, $PtCu_5$ compound with a maximum transformation temperature is formed in the region of concentrations from 25 to 62 atomic percent copper." *U.S. Joint Pub. Res. Service Rpt.* 469, *Soviet Abstracts Physics*, June 4, 1958.

967. Rudnitskii, A. A. and Polyakova, R. S. **Physical properties of ruthenium.** *Zhurn. Neorg. Khim.* no. **12**: 2758–2761, 1957.

In Russian.

"A study of a series of physical properties of Ru specimens (of purity ~ 99·8%), produced by a metalloceramic method, has been carried out. The following have been studied: specific gravity (11·90), microstructure and lattice parameters (a = 2·7015, c = 4·27604 A, c/a = 1·5828); the hardness, specific electric resistance of annealed specimens (7·427 Ω cm at 25°) and its temperature coefficient ($3·589 \times 10^{-3}$/degree) have been determined; in the heating curve of a specimen of Ru and in curves representing the relationship between the thermo-emf and temperature no anomalies are observed up to 1250°. On this basis it is assumed that there are no polymorphic changes in Ru up to 1250°." (*J. Abs. Metal.* nos. 5 and 6, 1958, p. 62).

968. Sakata, Toshimichi. **Some experimental studies of the conductivity and thermoelectromotive force of Cs_3Sb photocathodes.** *Phys. Soc. Japan J.* **8**: 125–126, Jan./Feb. 1953.

Experimental results are shown graphically. The thermo-emf ranges from 1·1 mV/deg. at 268 to 0·3 mV/deg. at 343°K. The resistivity is given by the formula $p = p_0 \exp(\varepsilon/kT)$, where T is the absolute temperature and ε is about 0·2–0·3, p-type conductivity being indicated.

969. Sakata, Toshimichi. **Some experimental studies of the conductivity and thermoelectromotive force of Cs_3Sb photocathodes. II.** *Phys. Soc. Japan J.* **8**: 272–273, Mar/Apr. 1953.

A note. The measurements were extended (from Part I) to 221°K. P-type conduction was observed over this range. The temperature variation of thermoelectric power indicated an impurity activation energy of about 0·4 eV in agreement with conduction measurements on the same cell. The acceptor levels are probably due to an excess of Sb.

970. Sakata, Toshimichi. **Thermoelectric power of cesium antimonide.** *Phys. Soc. Japan J.* **9**: 1031–1032, 1954.

The thermo-emf of Cs_3Sb specimens was determined and compared with values calculated from the expressions of Johnson and Lark-Horovitz which involved the Hall coefficient. Qualitative agreement between experiment and theory was obtained.

971. Samsonov, G. V. **Electric conductivity of some compounds of transition metals with Boron, carbon, nitrogen, and their melts.** *Zhurn. Tekh. Fiz.* **26**: 715–722, 1956.

In Russian.

Trans. in *Soviet Phys. Tech. Phys.* **1**: 695–701, 1957.

Data on the electric conductivity of TiB_2, TiC, TiN, ZrB_2, ZrC, ZrN, NbB_2, NbC, NbN, TaB_2, TaC, TaN, HfB_2, HfC, HfN, VB_2, VC, VN, Mo_2B_5, Mo_2C, MoN, Mo_2N, W_2B_5, WC, W_2N, LaB_6, and CeB_6, as well as of intermediate mixtures, are shown. At least qualitatively, the specific electrical resistivity of these substances can be interpreted in terms of the degree of incompleteness of the d or f electron levels of the corresponding metals.

972. SAMSONOV, H. V. and STRIEL'NIKOVA, N. S. **On the thermoelectromotive force on some metallic borides and carbides in contact with copper.** *Ukrain. Fiz. Zhurn.* **3**: 135–138, Jan./Feb. 1958.

In Russian.

The thermoelectromotive force of a number of metallic borides and carbides in contact with copper was measured in connection with a study of the physical nature of metallic phases. Among the compounds investigated were TiB_2, ZrB_2, Mo_2B_5, VB_2, CeB_6, NBd_6, PrB_6, TiC, ZrC, Mo_2C and VC. It was observed that the coefficient of the thermoelectromotive force of the borides is lower than that of the carbides, and that the coefficient of both borides and carbides decreases as the d level of the metal becomes filled. An interpretation of this regular dependence is proposed.

Air Intelligence Tech. Center Translation F-TS-9800/V is available.

973. SALKOVITZ, E. I. and KAMMER, E. W. **Thermoelectric power of dilute indium tin alloys.** *Am. Phys. Soc. Bull.* **2**: 339, 1957.

Abstract only.

"Concerns measurements made on a series of dilute indium-tin alloys from 77°K to room temperature. For alloys containing 1·5 atomic percent tin or less the thermal emf's measured relative to pure indium go through minima followed by maxima, the magnitudes of which depend upon composition. Alloys richer in tin, up to at least 2·9 atomic per cent, do not show the minima but do show the maxima. At 77°K the relative thermoelectric power is approximately linear with composition. As the temperature is raised, however, the thermoelectric power goes through a minimum. The higher the temperature, the higher is the tin composition at which the minimum occurs. In making the measurements considerable care has been exercised to avoid the effect of tension upon the samples, which are very soft. In some cases the tension coefficient of the thermoelectric power has actually been measured and found to be significant." Entire item quoted.

974. SASAKI, W. and KUNO, M. **On the effective mass of the conduction electron in germanium.** *Phys. Soc. Japan J.* **8**: 791–792, Nov./Dec. 1953.

Determinations based on Hall effect and thermoelectric measurements on n-type single crystals are tabulated and compared with results obtained by Debye and Conwell.

975. SASAKI, W., SAKAMOTO, N. and KUNO, M. **Some electrical properties of aluminium antimonide.** *Phys. Soc. Japan J.* **9**: 650–651, 1954.

AlSb ingot prepared by fusion of equimolar quantities of Al and Sb, and purified by passing four molten zones in an argon atmosphere. Due to evaporation of Sb during zone refining, the Al, component is probably in excess near the tail of the ingot. Specimens cut and examined for electrical homogeneity. The Te power can be calculated from the Hall data when a model is proposed for the energy bands and the scattering process of the charge carriers of the semiconductor. The scattering of the points on the plot is caused either by lattice vibrations or by the ionised impurities, and they lie between the two curves drawn corresponding to these two causes.

976. SATO, T. **Effects of the transformation process on the thermoelectric power of the superlattice alloy Cu_3Au.** *Phys. Soc. Japan J.* **5**: 268–272, Jly./Aug. 1950.

Pure Au and electrolytic Cu were melted together in a graphite tube and cast in to a wire 1 mm diameter and t cm long which was annealed at 800°C for 2 hours and slowly cooled for 15 hours. Resistance of the specimens was measured during heating and cooling using a current-potential method. From changes of resistance during heating and cooling the transformation temperature was found to lie between 375 and 392°C. The thermoelectric power against Pt was measured (value between 20 and 25 $\mu V\ deg^{-1}C$) and showed a maximum between 390 and 400°C. The peaks correspond to the anomalous resistance region just above the transformation temperature. The sign of the absolute thermoelectric power of the Cu_3Au superlattice alloy is positive in both ordered and disordered states, which result is not consistent with the sign of the Hall coefficient The results are discussed in terms of zone theory.

977. SATO, TAKAO and NOGUCHI, SEIICHIRO. **Note on some properties of gamma-brass.** *Phys. Soc. Japan J.* **12**: 335–338, 1957.

Resistivity, Hall coefficient, thermoelectric power, and magnetoresistance were measured for brasses with 31·5, 33·3, 35·3, 38·0, and 41·6% Cu. A minimum was observed in the resistivity at 34%. The Hall coefficient, thermoelectric power, and magnetoresistance were found to be comparable with metals. The results are discussed and compared with Bi.

978. SATO, T. **Notes on the thermoelectric properties of bismuth.** *Phys. Soc. Japan J.* **6**: 125–127, Mar./Apr. 1951.

Note: Experimental results on the thermoelectric power, and its variation with temperature, of pure Bi and of Bi containing 0·2 atomic-% of Sn, are reported. The value for Bi is about twice that for the alloy over the temperature range 0–200°C, the room temperature values are 0·06 and 0·16 mV/°C, and each material shows a maximum value at about 50°C.

979. SATO, TOMOO; KANEKO, HIDEO and SUDO, HAMIME. **Physical and chemical properties of malleable titanium.** *Tohoku Univ. Res. Inst. Mineral Dressing Met., Bull.* **8**: 105–107, 1952.

Not examined.

"The sample of malleable pure Ti was prepared by Hunter's method and its physical properties, such as specific gravity, hardness, tensile strength, elongation, recrystallisation temperature, trans-

formation point, lattice constant, specific heat, expansion coefficient, thermal conductivity, electrical conductivity and thermoelectromotive force, were measured to examine the previously published data. The corrosion tests showed that Ti was highly resistant to corrosion with ordinary reagents but was especially corroded with HCl and HF solutions. The electrochemical tests showed that Ti was easily made passive in phosphoric acid solution." *Chem. Abs.* **49**: 6061, 1955.

980. SATO, T. **Some properties of NiMn alloys of intermediate composition. I.** *Phys. Soc. Japan. J.* **6**: 223–227, Jly./Aug. 1951.

Measurements were made on both annealed and quenched specimens of the variation with temperature T both of the electrical resistance R of alloys of 47 and of 50 at. % Mn, and of the thermoelectric power against Pt of 47 at. % alloys. Results are presented graphically. The difference in R at room temperature between quenched and annealed specimens is very small for 47 at. % alloys, but for 50 at. % R (quenched) ~ 1·8 R (annealed). All specimens show a large and negative temperature coefficient of resistance and an anomalous behaviour in the thermoelectric power in the T range ~ 500–700°C. This is thought to be due to some electronic feature of the α–*B* Mn transformation (T_{7r} ~ 700°C) still remaining in the alloys of Mn with Ni, although these themselves show no structural changes in the temperature range studied.

981. SATO, T. **Thermoelectric properties of Bi,** *Phys. Soc. Japan. J.* **6**: 125–127, Mar./Apr. 1951.

Variation with temperature of dE/dT, of pure Bi, and Bi containing 0·2 atomic % of Sn. The value for Bi is about twice that for the alloy from 0–200°C. Room temperature values are 0·06 and 0·16 mV/°C, and each shows maximum value at about 50°C.

982. SATTERTHWAITE, C. B. and URE, R. W., JR. **Electrical and thermal properties of Bi_2Te_3.** *Phys. Rev.* **108**: 1164–1170, Dec. 1, 1957.

From thermal conductivity measurements over the temperature range 77–380°K, the lattice conductivity was found. The sharp rise in the thermal conductivity at room temperature was attributed to transport of energy by ambipolar diffusion of electrons and holes.

983. SAVORNIN, JEAN and SAVORNIN, FRANCE. **Contribution to the study of the thermoelectric properties of thin aluminium films.** *J. Phys. et Radium.* **17**: 283–286, Mar. 1956.

In French.

The thermoelectric properties of thin aluminium films evaporated on glass bases have been studied. The junctions of two constantan-copper thermocouples have been fastened on both ends of the layer; a potentiometer indicates the emf of the aluminium-copper thermocouple. The samples h icker than 100 millimicrons show about the same thermoelectric power as the massive metal itself. A non-important "thermal evolution" sometimes appears. The thermoelectric voltage of films, the thickness of which is comprised between 10 and 100 millimicrons, rises suddenly up to 0·1 V, for temperatures increasing with the thickness of the sample. A similar rise is observed when the thin film is connected to silver wires.

984. SAVORNIN, JEAN and SAVORNIN, FRANCE. **Discontinuities in the thermoelectric properties of thin metallic films.** *Acad. Sci. Paris. Compt. Rend.* **240**: 850–852, Feb. 21, 1955.

In French.

Continuing previous work the thermoelectric power of thin films of aluminium was studied. As the temperature of the hot junction was raised the film gave the same results as a thick sheet up to about 100°C, after which the thermoelectric power increases rapidly. On lowering the temperature and repeating the experiment, the temperature at which the abnormal increase set in usually became progressively higher. Though the experiments were conducted in air, there is reason to think the effect is not due to oxidation. Further work is in progress.

985. SAVORNIN, FRANCE. **Effect of thickness on the resistivity and the thermoelectric power of thin cobalt films.** *Acad. Sci. Paris. Compt. Rend.* **246**: 2866–2869, May 19, 1958.

In French.

Thin layers of cobalt were prepared by thermal evaporation in vaccum on glass backing at room temperature or at 175°C. The resistance was measured at room temperature as a function of the thickness of the cobalt film, and it was found that the resistance decreases when the thickness increases and is stabilised at a film thickness of about 200 to 300 A. The thermoelectric capacity varies with the thickness, increasing with the thickness and passing through a maximum.

986. SAVORNIN, FRANCE. **Influence de l'espaisseur sur la force electromotrice thermoelectrique de lames minces d'aluminum et de cobalt. (Effect of thickness on the electromotive thermoelectric force of thin aluminium and cobalt films.)** *Acad. Sci. Paris. Compt. Rend.* **245**: 147–149, Jly. 8, 1957.

In French.

Studies of vapour-deposited Al and Co films. The thermoelectric forces were increased by oxidation of the metal. Effect of oxidation was much smaller on the Co coatings.

987. SAVORNIN, JEAN and SAVORNIN, FRANCE. **The sign of the thermal emf of silicon.** *Acad. Sci. Paris. Compt. Rend.* **234**: 2165–2167, May 26, 1952.

In French.

Experiments carried out on small bars of Si (98% Si, 1·4% Al, 0·6% Fe), with Cu and constantan contacts at the ends, show that the thermal emf of Si with respect to Cu is positive, not negative, as given in tables of physical constants.

For a Si–Pb couple the thermal emf is 408μV/1°C, as against 80μV/1°C for a Pb–Bi couple.

988. SAVORNIN, JEAN and POGGI, A. **Au sujet des proprietes thermoelectriques du bismuth. (On the subject of the thermoelectric properties of bismuth).** *Acad. Sci. Paris, Compt. Rend.* **238**: 656, 1954.

In French.

The thermoelectric power of Bi/Cu couples decreases monotonically with increasing temperature in the range 10 to 230°C. The value is of order 60–70 × 10^{-6} volts/degree and is independent of the temperature difference used in the measurements.

989. SAVORNIN, JEAN and SAVORNIN, FRANCE. **Thermoelectric measurements on p-type silicon.** *Acad. Sci. Paris. Compt. Rend.* **235**: 465–467, Aug. 18, 1952.

In French.

The thermoelectric power, positive with respect to Cu, is about 700μv/1°C for material of purity 99·85%, falling to about 550μv/1°C for 99·4% purity and rising again to 590μv/1°C for 98% purity.

990. SAVORNIN, JEAN and SAVORNIN, FRANCE. **Thermoelectric power for very small differences of temperature.** *Acad. Sci. Paris. Compt. Rend.* **236**: 898–900, Mar. 2, 1953.

In French.

Measurements of the thermoelectric power dE/dT of a sample of p-type Si at temperatures near 15°C, with progressively smaller values of dT, show that the values obtained are constant, even when dT is as low as 0·01°. This result differs from that of Sato for a semiconducting Bi-Sn alloy, for which dE/dT for a temperature difference of 0·5 was only 75% of the value for a difference of 3°.

991. SAVORNIN, JEAN and COUCHET, G. **The thermoelectric power of aluminum in thin films.** *Acad. Sci. Paris. Compt. Rend.* **234**: 1608–1610, Apr. 16, 1952.

In French.

The thermoelectric couple consisted of a Cu wire and a film of Al vaporised on to a sheet of glass in vacuo. The cold junction was at 0°C and the hot junction at temperatures varying from 15°C to 300°C. The thermoelectric power was found to be independent of thickness in the range 10mμ to 1μ. The value was 4·00 ± 0·10 μV/°C at 0°C.

992. SAVORNIN, JEAN and SAVORNIN, FRANCE. **Thermoelectric properties of silicon and bismuth.** *Compt. Rend.* 79th Congr. Soc. Savantes Paris et Depts., Sect. Sci., Alger. 1954, 0. 39–43.

Not examined.

"The thermoelectric power of Si between 0–325° was investigated. At 20° the thermoelectric capacity of p Si exceeds 600 μV/degrees. The thermoelectric capacity of p Si was measured for small variations of temperature and compared with that of Bi semiconductors. For both Si–Cu and Bi–Cu the thermoelectric capacity is independent of the temperature difference. Measurements were also made of the thermoelectric capacity of the Bi–Cu couple at temperatures from 0–220°. The results agree with those of other authors." *Chem. Abs.* **51**: 10222, 1957.

993. SAVORNIN, FRANCE. **The thermoelectric electromotive force of very thin aluminum foils under vacuum.** *Acad. Sci. Paris. Compt. Rend.* **242**: 1969–1971, 1956.

In French.

A special apparatus was constructed to measure the emf of the following couples: (1) Ag/thin Al foil/Ag and (2) Ag/constantan/Ag. The thin Ag foil was placed in a small furnace and the resistance of the foil in circuit (1) was measured. Then the extremity of the foil was heated to above 200° and simultaneously the emf of the couples were measured potentiometrically. A table shows the emf to be independent of the weight of the foil tested unless the temperature of testing is above 200°.

994. SCHILLING, H. **Measurements of the thermoelectric power of copper oxide (Cu_2O) in the single phase region.** *Ann. Physik.* **16**: 84–92, 1955.

Reports measurements between 500° and 1025°C and at O_2 pressures between 100 and 4 × 10^{-5} mm. Hg. The measurements show the oxide to be a defect conductor over the whole range.

995. SCHMIDT, HANS-EBERHARD. **Leitfaehigheit und hallkonstante. IX. Eine methode zur getrennten bestimmung der dichte und beweglichkeit von ladungstraegern verschiedenen vorzeichens in metallen. (Electrical conductivity and the Hall coefficient. IX. A method for the separate determination of density and mobility of the charge carriers of different sign in metals).** *Z. Metallk.* **49**: 113–123, Mar. 1958.

In German,

Measurements of electrical conductivity, Hall coefficient, absolute thermoelectric power, and Ettingshausen-Nernst coefficient in Ag–Pd, Cu–Ni, Cu–Au, and Ni–Cr alloys.

996. SEMENKOVICH, S. A. and ASTASHEV, N. N. **Vozgonka tellura. (Sublimation of tellurium).** *Zhurn. Tekh. Fiz.* **28**: 725–732, Apr. 1958.

In Russian.

Translation appears in Infosearch Tech. Lit. Info. Serv. Russian Lit. Survey SEM-5-58, p. 8·1–8·8.

A simple procedure for purifying crude tellurium (98·5–99·0% TE) by sublimation (0·3–0·7 kg/hr in 1·5–2·5 kg batches) is described. The purified tellurium may be used for thermoelements.

997. SEKIGUCHI, TOSHIYUKI. **Physical properties of selenium. III. Thermoelectric power.** *Kagaku Kenkyusho Hokoku.* **32**: 191–196, 1956.

In Japanese. Not examined.

"Thermoelectric power of microcrystalline hexagonal Se and its temperature dependence

were observed. Applying these values to usual formulas, S. calculated the d. of charge carriers (pos. holes) at each temperature. The d. of holes decreased with rise in temperature in the temperature region from room temperature to about 70°. This caused a decrease in conductivity with rising temperature. The results show that the impurity levels of hexagonal Se are already totally ionised at room temperature and are due principally not to chemical impurities but to lattice defects." *Chem. Abs.* **52**: 19, 1958.

998. SEMENOVA, N. V. **On the anomalous electric conductivity of Ni_3Cr.** *Fiz. Met. i Metalloved.* **6**: 1017–1026, 1958.

In Russian.

The microstructure, volume alterations lattice, period, thermoelectromotive forces, and harness of Michrome alloys of various thermal treatments were studied in order to determine the anomalous changes in the electric resistance of the alloys. The data obtained show that the structural process appearing in the binary Ni_3Cr alloy and ternary Ni_3(Cr, Mo) and Ni_3(Cr, V) alloys at 400–500°C are followed by an increase of thermoelectromotive forces which leads to assumption that this structural process is an atomic ordering not yet investigated in the transition group elements.

999. SEMILETOV, S. A. and PINSKER, Z. G. **Electronographic investigation of the bismuth-selenium system of alloys.** *Akad. Nauk. SSSR. Dok.* **100**: 1079–1082, 1955.

In Russian.

Two rhombohedral compounds, Bi_2Se_3 and BiSe and a 3rd, fcc Bi_3Se_4, not previously reported, were identified, and lattice dimensions measured. Measurements of many electronograms indicate that dimensions of the unit cells vary within considerable limits. This is ascribed to formation of solid solutions with the components and it is surmised that the structures of Bi_2Se_3, Bi_3Se_4, and BiSe differ only in the number of octahedral voids filled by, thus: (1) 2/3 of the voids filled by Bi atoms; (2) 3/4 of the voids filled. Special experiments indicate that this theory agrees with the facts that adding Bi expands the unit cells and addition of Se contracts them.

1000. SEMILETOV, S. A. **Electronographic investigation of the structure of sublimed films of the composition Bi-Se and Bi-Te.** *Inst. Krist. Akad. Nauk. SSSR. Trudy.* **10**: 76–83, 1954.

In Russian.

Electron diffraction studies of 10^{-5} to 10^{-6} cm. thick films on NaCl, mica, celluloid, or glass. Method of inclined texture was used. Rhombohedral phases Bi_2Se_3 and Bi_3Se_4 and the cubic phase of BiSe occur in the Bi-Se system. Details are given of the structural parameters of the two systems.

1001. SEMILETOV, S. A. and PINSKER, Z. G. **Oxidation of samples of Bi_2Se_3 and Bi_2Te_3 when annealed in air.** *Zhurn. Tekh. Fiz.* **25**: 2336–2338 1955.

In Russian.

Annealing done at 200°C for up to 30 minutes. Electronogram measurements indicate a decrease in the lattice period with increased time of heating, i.e., the solid solutions of Bi_2(Se, O)$_3$ and Bi(S, O) are formed. Similar observations were made on Bi_2Te_3. The (111) and (112) faces of BiO form parallel to the (0001) and (1120) faces of the decomposing Bi_2Te_3.

1002. SEROVA, F. G. **Thermoelectric properties of monovalent metals.** *Zhurn. Eksp. v. Teor. Fiz.* **19**: 460–468, May 1949.

In Russian.

The Thomson coefficient p at high temperatures of Li and Na is calculated, considering the effect of electrons transported by a current of phonons; the substantially different kind of dependence of the mean free path of the electrons on the energy compared with that of free electrons is pointed out. A positive value of p is found, in agreement with the experimental data for Li. The calculations show that the positive value of p is due to the "transport" effect. For Na the effect is not appreciable.

1003. SHAPIRO, I. P. **On the question of the thermoelectric power of selenium.** *Zhurn. Tekh. Fiz.* **21**: 717–719, 1952.

In Russian.

Crystalline Se, heated from 18°C to 60°C, approximately doubled its thermoelectric power, which also fell to zero after 80 minutes in the presence of Hg vapour at 50°C. The cause of these phenomena is discussed.

1004. SHAW, W. C., HUDSON, D. E. and DANIELSON, G. C. **Electrical properties of boron single crystals.** *Phys. Rev.* **107**: 419–427, Jly. 15, 1957.

Electrical resistivity, Hall coefficient, and thermo electric power of microscopic crystals were measured as a function of temperature. Rectification and photoconductivity effects were observed at room temperature.

1005. SHIGETOMI, SHIGENOBU and SIGEYASU, MORI. **Electrical properties of Bi_2Te_3.** *Phys. Soc. Japan J.* **11**: 915–919, Sept. 1956.

The conductivity, Hall coefficient and thermoelectric power of the compound Bi_2Te_3 are measured over the temperature range from 100°K to 750°K. Specimens used show electrical conduction of p-type at toom temperature and the hole mobility dependence is represented by the relation $\mu_h = 1{\cdot}2 \times 10^8 T^{-2{\cdot}3}$. It is found that the forbidden energy gap Eg is 0·21 eV at 0°K and the effective masses of holes and electrons are, respectively, 1·26 *m* and 1·07 *m*, and the mobility ratio *b* is about 1·7.

1006. SHIRAKAWA, Y., OHARA, T. and AMEMIYA, D. **Thermocouples with non-linear characteristics**

composed of Fe-Al-Cr and Cu-Ni alloys. *Nippon Kinzoku.* **20**: 131–135, Mar. 1956.

"Thermal emf's were measured for Fe–Al, Fe–Cr, Fe–Al–Cr and Cu–Ni couples between 100 and 800°C. A couple formed between Cu-1·94% Ni and Fe-6·2% Al-0·94% Cr alloys has an emf which is almost zero between room temperature and 400°C and then increases to 5·4 mV at 800°C." *J. Iron & Steel Inst.* **191**: 86, Jan. 1959.

1007. SHTENBECK, M. and BARANSKII, P. I. **Experimental study of the relationship between the Peltier effect and thermo-emf in germanium.** *Zhurn. Tekh. Fiz.* **27**: 233–237, Feb. 1957.

In Russian.

Translation in *Soviet Phys. Tech. Phys.* **2**: 205–209, Feb. 1957.

The results of experiments carried out at 160–400°K on n- and p-type Ge confirmed the conclusions reached by the same authors in their earlier work. The Peltier coefficient $P \neq \alpha T$ (α = thermo-emf, T = absolute temperature) in the extrinsic range, while in the intrinsic range $P \neq \alpha T$, The specific heat, C, of the carrier (electron and hole) gas determined from the data on $P \neq P(T)$, in contrast to data on $\alpha = \alpha(T)$, was in good agreement with C of the classical ideal gas = 3/2k.

1008. SHTENBECK, M. and BARANSKII, P. I. **Investigation of Peltier effect and thermoelectromotive forces in germanium.** *Zhurn. Tekh. Fiz.* **26**: 683–685, Mar. 1956.

In Russian.

Translation in *Acad. Sci. USSR. Bull. Phys. Ser.* **20**: 1368–1369, 1956. Also in Infosearch Tech. Lit. Info. Serv. Russian Lit. Survey SEM-1-56, p. 4·1–4·3.

The fundamental equations (1) and (2) relating to the Peltier heat, Thomson coefficient and differential thermoemf to one another do not necessarily follow from the first two laws of thermodynamics and therefore the first two of these quantities cannot be determined uniquely from measured values of the thermo-emf. A method has been developed for direct measurement of the Peltier heat at a Ge–Cu contact. Some experimental curves are shown, and theoretical implications are discussed.

1009. SIDYAKIN, V. G. **Electrical properties of selenium with gold impurity.** *Soviet Phys. Solid State.* **1**: 1073–1075, Feb. 1960.

Measurements of the thermoelectric power showed that the conductivity in selenium with gold as an impurity is electronic in nature. Table 3, p. 1075, gives the thermoelectric power values at 35 C. The value of the thermoelectric power a rises slightly with increase of temperature, but the temperature dependence of a is not affected by the amount of gold in Se.

1010. SILVERMAN, S. J. **Electrical properties of single crystals and thin films of PbSe and PbTe.** *Phys. Rev.* **94**: 871–876, May 15, 1954.

Comparison of electrical properties of single crystals and films; Hall constants and resistivities as functions of temperature between 77 and 300°K; effects of experimental variables on carrier mobilities on thin films.

1011. SINANIM, S. S. and GORDYAKOVA, G. N. **Solid solutions of Bi_2Te_3-Bi_2Se_3 as materials for thermoelements.** *Zhurn. Tekh. Fiz.* **26**: 2398–2399, 1956.

In Russian.

Translation in Infosearch Tech. Lit. Info. Serv. Russian Lit. Survey SEM-2-57: 5·1–5·2, 1957.

Briefly reports the results of an investigation of the thermoelectric properties of solid solutions based on two similar compounds, both in chemical and structural respect.

1012. **Single-crystal semiconductor.** *Engrs. Dig.* **20:** A8, Jly. 1959.

"Stated to have thermoelectric properties which can provide an economical means of producing electricity directly, a new single-crystal semiconductor of unspecified composition has been patented by Semi-Elements, Inc., of Saxonburgh, Pa. It is claimed that the material can be mass-produced in large sizes and that, at present, a ½-in. crystal is capable of producing a 25 mA at 0·25 V at temperatures around 70·F, or more than 100 mA at 1V at 300°F. It is also stated that the new material can pass current in one direction and prevent it flowing in another without the need for any junction or special preparation." Entire item quoted.

1013. SKANAVI, G. L. and KASHTANOVA, A. M. **The production of semiconducting ceramics based on WO_3 and a study of some of their electrical and thermal properties.** *Zhurn. Tekh. Fiz.* **25**: 1883–1892, 1955.

In Russian.

Trans. 59–10140 available from Translation Center, Special Libraries Association, Crerar Library, Chicago, Ill.

Specimens of fully sintered semiconducting ceramics based on WO_3 have been obtained. The results of electrical and thermoelectric measurements as well as of determinations of the thermal conductivity of these materials are reported.

1014. SMITH, R. A. **The electronic and optical properties of the lead sulphide group of semiconductors.** *Physica.* **20**: 910–929, 1954.

Also in Conference on Semiconductors, Amsterdam, 1954. Proceedings, p. 910–929.

Measurement of thermoelectric and thermomagnetic effects, p. 926–927.

1015. SMIROUS, K. and STORAC, L. **Feste Losungen von Bi_2Te_3 und Sb_2Te_3 als p-leitende werkstaffe fur halbleiter-thermoelemente. (Solid solutions of Bi_2, Te_3 and Sb_2Te_3 as p-conducting materials for semiconductor thermoelectric cells).** *Z. Naturforsch.* **14a**: 848–849, 1959.

In German.

For English summary see *Chem. Abs.* **54**: 5261, Mar. 25, 1960. Translation available from Associated Electrical Indus., Aldermaston, Berkshire, Eng.

1016. SOCHTIG, H. **Untersuchungen an reinem chromim anomaliegebiet. Elektrischer und thermischer widerstand, thermokraft, waermetoenung, magnetische suszeptibilitaet und gitterstruktur. (Investigations of pure chromium in the region of anomaly. Electric and thermal resistance, thermoelectric power, evolution of heat, magnetic susceptibility and lattice structure).** *Ann. Physik.* **38**: 97–120, 1940.

In German.

The thermal conductivity of pure Cr was determined by the stationary heat-flow method.

1017. SOKOL'SKAIA, I. L. **On intermetallic alloys of platinum and gold with alkali and alkaline earth metals.** *Zhurn. Tekh. Fiz.* **27**: 127–129, 1957.

In Russian.

Translation in *Soviet Phys. Tech. Phys.* **2**: 108–110, 1957.

Electrical conductivity and electrical and thermoelectric properties of the systems Na–Au, Na–Pt and Ba–Pt.

1018. Stanford Research Institute, Menlo Park, Calif. **Thermoelectric materials,** by J. W. JOHNSON 5 issues, 1959. (Bimon. Prog. Rept. 1, 2, 3, 4, 5) (Contract NObs-77017) (AD-212 673).

Solid and liquid materials are to be evaluated for possible use as elements for thermoelectric generators.

1019. STAUSS, H. E. **Electric and magnetic alloys.** *In U.S. Nav. Res. Lab. Rept. NRL. Lrog.* p. 55, Aug. 1959.

Concerns the locale of Peltier effects in thermoelements.

1020. STEELE, M. C. **Magnetic field dependence of the Seebeck effect in germanium.** *Phys. Rev.* **107**: 81–83, Jly. 1, 1957.

The thermoelectric power (Seebeck effect) of n-type Ge singlecry stals, measured at 78–278°K, increased with the applied magnetic field, the maximum value of which was 11,500 Oe. This agrees with theoretical predictions and is consistent with a simplified model of a semiconductor. The absence of any magnetic field-dependence of the thermal conductivity confirms the results of previous workers.

1021. STEELE, M. C. **Magnetic field dependence of the thermoelectric power of germanium.** *Semiconductor Abs.* **4**: 105, 1956.

Abstract only of paper given at American Physical Society Meeting, Washington, D.C., April 26–28, 1956.

"The thermoelectric power of an n-type Ge single crystal (10 ohm cm resistivity) has been measured at several temperatures as a function of magnetic field strengths up to 11,500 gauss. The heating current was parallel to a 111 axis, while H, applied magnetic field, was perpendicular to the heat current. At 78°K, Q, the thermoelectric power, increased in magnitude (became more negative for the n-type crystal used) from −1990 to −2970 microvolts/°K, as H went from 0 to 11,500 gauss. At low fields (up to about 2500 gauss), Q increased as H^2, but at higher fields saturation effects became evident. Measurements at 236°K revealed an increase of only 2% in Q for a field of 11,500 gauss. These results are in keeping with a phenomenological low field treatment of the effect which predicts that $\triangle Q/Q_0$, the relative change in Q, should be proportional to $(\mu H)^2$, where μ is the mobility." Entire item quoted.

1022. STEELE, M. C. and BABISKIN, J. **Oscillatory thermomagnetic properties of a bismuth single crystal at liquid helium temperatures.** *Phys. Rev.* **98**: 359–367, 1955.

TE power, thermal conductivity and electrical resistance measured on a Bi single crystal in magnetic fields up to 13 kilogausses at liquid He temperatures. The results for two newly discovered effects, the oscillatory magnetic field dependence of both the TE power and the thermal conductivity are presented in detail. Temperature and field dependence of the amplitude of oscillatory effects are discussed.

1023. STEELE, M. C. and ROSI, F. D. **Thermal conductivity and thermoelectric power of germanium silicon alloys.** *J. Appl. Phys.* **29**: 1517–1520, figs., Nov. 1958.

Thermal conductivity measurements have been made on a series of germanium-silicon alloys. At 300°K for an alloy containing 56 atomic percent Si, the thermal conductivity was found to be six times smaller than the value for pure Ge Measurements of the thermoelectric power on some alloys are also reported. It is then shown that solid-solution alloying can significantly increase the figure of merit of thermoelectric materials.

1024. STEPHENS, E. **The Hall effect, electrical conductivity, and thermoelectric power of the lead-antimony series of alloys.** *Phil. Mag.* **9**: 547–560, 1930.

The thermoelectric power with respect to lead of antimony–lead alloy varies with its composition between zero and + 40 microvolts per degree centigrade. Thermo-emf of Sb with respect to Cu is 38 V/°C. Also, has resistivity tables for alloys before and after annealing. Annealing produces a diminution in resistivity of all the alloys.

1025. STONE, B. and HILL, D. **Preparation and semiconducting properties of single crystal boron phosphide.** *Am. Phys. Soc. Bull.* **4**: 408, Nov. 27, 1959.

Abstract of paper.

Thermoelectric power measurements show that both n- and p-type material has been prepared.

Measurements of Hall coefficient on p-type material indicate a carrier concentration of about 10^{18} carriers/cm^3.

1026. STONEBURNER, D. F., YANG, LING, and DERGE, G. **Measurement of the thermoelectric power on several molten sulfide-solid tungsten thermocouples.** *Am. Inst. Mining Engrs. Met. Soc. Trans.* **215**: 879–880, figs., Oct. 1959.

Thermoelectric power of copper sulfide (nominally stoichiometric), copper sulfide (copper rich), iron sulfide (iron rich), silver sulfide, and lead sulfide is shown in table 1.

1027. SUZUKI, HASUMASA; ENDO, SHIGEAKI, and HAGA, EIJIRO. **Thermoelectric power of silver chloride.** *Phys. Soc. Japan. J.* **14**: 729–731, 1959.

Thermoelectric power of AgCl doped with $CdCl_2$ concentrations of 0·008, 0·022, 0·068, 0·16, and 0·20 mole-% was measured. Results in mv/degree for temperatures to 440° agree well with theory.

1028. SUGE, YOSHIO and AOKI, MASAHARU. **The thermoelectric properties of bismuth telluride.** *Oyo Butsuri.* **27**: 767, 1958.

Not examined.

"By use of impurity-doped n-type and p-type Bi_2Te_3 a temperature difference 72·2° was attained with the warm junction held at 51·1° through application of the optimum intensity of the electric current. The thermo-emf of the sample used was 194 micro/degree, −174 microv./degree, its electric conductivity 770 ohm^{-1} -cm.$^{-1}$, 1430 ohm.$^{-1}$. cm.$^{-1}$, its thermal conductivity 0·019 W./cm.-degree, 0·021W./cm.-degree for the p-and n-type, respectively." *Chem. Abs.* **53**: 6779, 1959.

1029. TAUC, JAN and MATYAS, MILOS. **The electric and thermoelectric properties of indium antimonide.** *Czechoslov. J. Phys.* **5**: 369–383, 1955.

In Russian.

Translation no. tr. −3510 available from the Atomic Energy Commission.

The electrical conductivity, Hall constant, and thermoelectric power are reported as functions of temperature for p-type crystals made by refining, and for n-type specimens made by doping p-type crystals with Se. Results in general agree with those obtained elsewhere. The position of the Fermi level is obtained from an analysis of thermoelectric data. The n-type samples are degenerate over the whole temperature range; the p-type samples at high temperatures (when intrinsic).

1030. TANUMA, SEIICHI. **Low temperature thermoelectric power of Cu-Mn alloys.** *Phys. Soc. Japan. J.* **14**: 541, Apr. 1959.

Reports measurements to verify fact that dilute alloys of copper with manganese show a minimum in the resistance–temperature curve in the low temperature region followed by a maximum in the lower temperatures, and suggests that perhaps the complicating factor entering into the nature of the resistance minimum in CuMn alloys is related to the magnetic properties of solute ions in this alloy.

1031. TANUMA, SEIICHI. **The effects of thermally produced lattice defects on the electrical properties of tellurium.** *Tohoku Univ. Res. Inst. Sci. Rpt. Ser.* **A6**: 159–171, 1954.

Electrical conductivity and Hall effect measurements used for investigation of composite semiconductors. The width of the forbidden energy band E, the effective masses of electrons and holes, m_e and m_h and the carrier mobilities due to lattice scattering were determined. The reversals of the Hall effect and TE power found in the pure intrinsic region are explained by the predominance of holes released from lattice defects. Their concentration increases with the rise of temperature.

1032. TAUTS, A. **Thermoelectric phenomena in semiconductors with non-uniform charge carrier concentration.** *Akad. Nauk. SSSR. Izvest. Ser. Fiz.* **20**: 1357-1360, 1956.

In Russian.

Thermal emf measured on a Ge single-crystal surface with a W point is quite different from the emf measured with flat electrodes because in this case a nonuniform distribution of holes tends to change the sign of the charge on the point contact. In this case the nonuniform distribution is due to a temperature gradient. In the region of the temperature drop the concentration of minority carriers is a nonequilibrium value which leads to a further correction for the observed emf. An experimental installation is described to determine the emf dependence on temperature gradient in Ge single crystals. A nonuniform hole concentration can also be produced by illumination. If illumination is combined with a temperature gradient, a new effect ("thermal photoeffect") is obtained. A photovoltaic voltage is obtained from a semiconductor in which a temperature gradient is produced.

English version with title **thermoelectric effects in semiconductors with nonequilibrium current-carrier concentrations appears in** *Acad. Sci. USSR. Bull. Phys. Ser.* **20**: 1357–1360, 1956.

1033. TAYLOR, J. C. and COLES, B. R. **Thermoelectric power in palladium-silver and palladium-rhodium alloys.** *Phys. Rev.* **102**: 27–30, Apr. 1, 1956.

TE power of Pd-Ag alloys was found highly sensitive to presence of unoccupied d-band states in range 77° to 273°K.; marked variation with composition was found in alloys with more than 90% of either element; also, measurements on Pd–rich Pd–Rh alloys.

1034. TELKES, MARIA. **Materials for solar thermoelectric converters.** *Conf. Uses Solar Energy Tucson*, 1955, *Trans.* **5**: 1–7, 1958.

The efficiencies of thermoelectric generators of

various thermoelectric materials are reviewed. Experimental results are tabulated on measurements of thermoelectric power, open-circuit emf, and observed and calculated efficiencies of three thermocouple combinations over the temperature ranges (T_h-T_c, °C) of 100–20, 200–20, and 400–20. The thermocouples are Chromel P-Constantan, ZnSb (Sn, Ag, Bi)-Constantan, and ZnSb (Sn, Ag, Bi)—91 Bi + 9 Sb. The last couple produced the greatest efficiency. 3·4% for a 180° temperature differential.

1035. TELKES, MARIA. **Thermoelectric alloy.** U.S. Patent no. 2,366,881, Jan. 9, 1945.

Addition of tin and silver in accurately controlled amounts to a zinc–antimony alloy of the approximate composition 35% Zn and 65% Sb.

1036. TELKES, MARIA. **Thermoelectric power and electric conductivity of lead sulfide.** *In* Conference on Physical Electronics. Report on Tenth Annual Conference, March 30, 31 and April 1, 1950 at the Massachusetts Institute of Technology, p. 52–55, Cambridge, Mass, 1950.

Reports a study of thermoelectric power and electric conductivity of lead sulfide on thin films used in photoconductivity cells.

1037. **Tellurium compounds for semiconductors.** *Electron.* **32**: 68, 70–71, Mar. 6, 1959.

Refers to recent work at Batelle which has shown some "interesting characteristics" for tellurium compounds.

1038. TENNERY, V. J. **Investigation of rare earth doped barium titanate.** *Dissertation Abs.* **20**: 1708, 1959.

Ph.D. dissertation, University of Illinois, 1959.

The effect upon the D.C. resistivity of barium titanate of additions of from 0·0015 to 0·0030 mole fraction of rare earth oxide was investigated. Thermoelectric probe measurements indicated that materials used, i.e., samarium, gadolium and holmium were n-type in the tetragonal phase. Thermoelectric power measurements were made by the difference method on the pure titanate and a representative gadolinium-doped sample as a function of temperature. At the tetragonal-cubic transition the semiconducting material changes from n-type to p-type. The sharp increase in resistivity is thus due to a decrease in the mobility of the electrons donated by the rare earth impurity to the titanium sub-lattice. A mechanism is proposed to explain this behaviour, wherein the excess electrons become trapped on a particular titanium ion when the material becomes cubic. As a result the Ti^{+3} ions then act as acceptors and introduce holes in the band structure which act as the charge carriers in the cubic phase. No measurable thermoelectric power was observed in the pure titanate. The thermoelectric power of the doped material is approximately 700 μV/°C in the tetragonal phase.

1039. TODAO, F. and SEIICHI, T. **Thermoelectric power of nonpolar semiconductor e.g., Te crystals.** *Tohoku, Univ. Res. Inst. Sci. Rpt. Ser. A.* **4**: 353, 1952.

Primarily theoretical.

1040. TOMASCH, W. J. **Structure in the thermoelectric power of dilute indium-lead alloys.** *Phys. Rev.* **109**: 69, Jan. 1, 1958.

Liquid N and ice temperature measurements of the thermoelectric power of dilute In–Pb alloys indicate that there is detailed structure superimposed on the smooth trend of the data.

1041. TOMASCH, W. J. and REITZ, J. R. **Thermoelectric power of dilute indium-lead and indium-thallium alloys.** *Phys. Rev.* **111**: 757–764, Aug. 1, 1958.

The investigation included 22 In-Pb alloys and 13 In-Tl alloys. For the In–Pb alloys, the existence of structure at both 273° and 77°K is reaffirmed. On the other hand, the thermoelectric power of the In-Tl system is found to be an extremely smooth function composition in the same range of solute concentration. As a consequence, it is concluded that the observed structure in In-Pb is due exclusively to changes in electronic concentration brought about by alloying.

1042. TOYODA, H. **Electrical properties of Carbon.** *Tanso* (*Carbons*). **2**: 224–232, 1952.

In Japanese. Not examined.

"The electrical resistance and the thermoelectric power of microphone C, made from anthracite or phenol-formaldehyde resin, were measured between 20° and 360°C. The resistance at 30°C varies depending on the baking temperature. For anthracite C, the resistance is 0·0086 ohm-cm, 0·013, 0·047, 0·39, 5·5, 1·5 × 10^3 and 5 × 10^4 for temperatures of 1000, 900, 800, 700, 650, 600 and 500°C, respectively. A similar change was measured for resin C. The temperature variation of resistance for anthracite carbon follows that for a semiconductor with the activation energy 0·013 e.v. (1000°C), 0·046 (800°C), 0·15 (700°C), 0·18 (650°C), and 0·34 (600°C). The thermoelectric power also confirms the intrinsic semiconductive mechanism. The Hall constant was too small to measure. The energy-band scheme of C is discussed." (*Semiconductor Abs.* **3**: 334, 1955).

1043. Transitron Electronic Corp. Wakefield, Mass. **Thermoelectric materials,** January 4—March 3, 1960. 12 p., Mar. 3, 1960. (*Bimon. Prog. Rept.* 1) (Contract NObs-78345).

Purpose of this contract is to develop and evaluate thermoelectric power generation materials in particular metal silicides, for use at temperatures up to 1,000°C and higher. To this end methods have been developed for the production of such refractory alloys and for the measurement of their pertinent thermoelectric properties.

Initial investigations have been in the direction of ternary additions to binary transitional silicides.

1044. TSUBOKAWA, ICHIRO. **The magnetic properties of chromium-tellurium-selenium system.** *Phys. Soc. Japan J.* **11**: 612–665, June 1956.

Study of change in magnetic properties due to replacement of Te by Se in CrTe which has NiAs structure. Ferromagnetism observed in concentration range x = 0 to 0·8 in Cr ($Te^{1-x}Se_x$). Compounds outside this range are para- or antiferromagnetic. In the paramagnetic range of temperature the Curie-Weiss law is found to be valid. It is also found that the Curie-Weiss constant is independent of concentration in the neighbourhood of CrTe and CrSe respectively, and varies abruptly at the transition concentration from ferro- to antiferromagnetic state. A short discussion is given.

1045. Tsuji, Mikio. **Transport phenomena in monovalent metals.** *Phys. Soc. Japan J.* **13**: 426, 1958.

A note. Formulae were obtained for the electrical and thermal conductivities and the absolute thermoelectric power which are approximately correct at all temperatures and for any concentration of impurities. The results are compared with those obtained by interpolation by Hanna and Sondheimer.

1046. Tyler, W. W. **Thermal conductivity, electrical resistivity of graphite.** *Phys. Rev.* **89**: 870–875, Feb. 15, 1953.

Subject properties measured in the range 20° to 300° K, for artificial extruded, material moulded, and lampblack graphite. Experimental results discussed in relation to theory.

1047. Ubbelohde, A. R. and Orr, J. **Anisotropic thermoelectric effects in graphite.** *Nature.* **179**: 193–194, Jan. 26, 1957.

The thermoelectric power of graphite/copper along the c-axis is ~ 30 μV/°C and ~ 11 μV/°C along the a-axis. The form of the relation was confirmed up to 1200°C using "self-couples" between blocks cut along the a- and c-axes respectively and carrying out the measurements in a reducing atmosphere. Oxygen had a marked effect on the values of thermoelectric power obtained.

1048. Udy, M. J. **Chromium. V.II. Metallurgy of Chromium and its Alloys.** 402 p., illus., New York, Reinhold, 1956.

Table 22.8. Thermoelectric power of chromium versus platinum, p. 107.

1049. Ukrainsky, Yu. M., Novoselova, A. V. and Simanov, Yu. N. **Investigation of the tantalum-tellurium system.** *Zhurn. Neorg. Khim.* **4**: 148–152, 1959.

In Russian.

Ta-Te alloys were prepared by sintering mixtures of Ta (NB 0·3, Ti 0·1%) and Te (99·99%) powders in sealed quartz ampoules at 800°C., and were examined by X-ray analysis and measurement of electrical conductivity (σ) and thermo-emf (α). Two compounds of variable composition are formed in the system; the α-phase $TaTe_{0.85-1.2}$ and the β-phase $TaTe_{1.5-2.0}$; there is also the compound $TaTe_3$, which has a tetragonal structure with lattice parameters a = 6·5, c = 11·8 kX, Z = 4. The σ/composition and α/composition curves exhibit maxima and minima, respectively, at points corresponding to $TaTe_3$, the values of σ and α show that $TaTe_3$ has semimetallic bands. There is a transformation in the α-phase at 840°C.

1050. Union Carbide Corp. Parma Research Laboratory, Parma, Ohio. **Thermoelectric materials.** Nov. 28, 1959 to Jan. 28, 1960, 33 p., Feb. 15, 1960. (*Bimon. Prog. Rept.* 6) (Contract NObs-77066).

The new method for production of rare earth nitrides described in the previous report is being successfully used in the preparation of a series of these compounds. Thus far, samarium nitride demonstrates the best combination of chemical stability and reasonable semiconductor properties and will merit further studies. The rectangular bar method for measurement of thermal conductivity of electrical conductive materials is being improved. Theoretical work on electronic properties of graphite has been carried to the point where it is possible to calculate the high temperature electrical resistivity and thermoelectric power of single crystals or well ordered graphite filaments with good agreement with the experimental data available.

1051. Urkov, V. A. and Alekseyeva, N. E. **Thermoelectric properties of Cd-Sb alloys.** *Zhurn. Tekh. Fiz.* **26**: 911–912, 1956.

In Russian.

A null method was used to measure the thermal emf of Cd–Sb alloys relative to Cu for concentrations of 0–100% Sb at junction temperatures of 10° to 100°C.

1052. U.S. Atomic Energy Commission, Oak Ridge National Laboratory, Oak Ridge, Tenn. **Solid state division annual progress report for period ending August 31, 1959.** 227 p., Dec. 11, 1959. (ORNL-2829).

Thermoelectric power in germanium. Report of progress on work undertaken by O. E. Schow, J. C. Pigg and C. C. Robinson. p. 129–131.

1053. U.S. Atomic Energy Commission, Washington, D.C. **The electrical properties of crystalline boron,** by W. C. Shaw, D. E. Hudson and G. C. Danielson. 152 p., 1953. (Rept. ISC-380).

Hall, thermoelectric and rectification studies showed that the purest specimens of crystalline B were predominantly p-type, but readily converted by heat-treatment to low-resistivity n-type crystals,

1054. U.S. Atomic Energy Commission, Washington, D.C. **Thermal and electrical properties of graphite irradiated at temperatures from 100 to 425°K,** by G. E. Deegan. 77 p., 1956. (Rpt. SR-1716).

Data were obtained for the thermoelectric power and electrical and thermal conductivity of graphite as a function of several proton irradiations (0·65–30 μ ah/sq.cm.) from 103 to 423°K. In general, irradiating at 300°K produced the same property

changes as irradiating at 103°K and then annealing to 300°K. For exposures greater than 5–10 μ ah/sq. cm., 423°K irradiations were appreciably less effective in producing property changes than 100°K. irradiation plus 423°K annealing. In pulse annealing of samples irradiated at 103°K, it was found that recovery of all properties was very marked at about 150°K and higher when room temperature was attained. In pulse annealing to higher temperatures the strong recovery state starting at about 400°K was attained. In comparing proton- with neutron-damaged samples, a correlation was found for the thermal and electrical conductivities but not for the thermoelectric power.

1055. U.S. Atomic Energy Commission, Washington, D.C. **Thermoelectric nuclear fuel element annual progress report,** by J. C. DANKO *et al.* 11 p., Apr. 15, 1959. (WCAP-1162).

Discusses the preparation and thermoelectric roperties of mixed valence materials.

1056. U.S. Atomic Energy Commission, Washington, D.C. **Thermoelectric nuclear fuel element,** by J. C. DANKO, *et al.* 30 p., Jly. 10, 1959. (Rept. WCAP-1245) (Quart. Prog. Rept. 1).

The radiation damage begins to anneal out for most materials reported on at fairly low temperatures as shown by the post-irradiation measurements.

1057. UST'YANOV, V. I. **The electrical properties of the system tin–antimony.** *Zhurn. Tekh. Fiz.* **28**: 1190–1194, 1958.

In Russian.

The conductivities σ, Hall constants R, and thermoelectric powers α of five alloys made from purified Sn and Sb in the range 55-65 weight percent Sn were measured (R at 25°C; α and σ, 25–330°C). Some of the alloys were two-phase. Values of α up to 100 μV deg./ C were obtained. The number of carriers/cm³ (~ 3×10^{20} electrons) diminished linearly with increasing Sb concentration. A qualitative interpretation of the results was attempted.

1058. VACHENYA, S. A. and DORFMAN, YA. **Thermoelectric properties of ferrites near curie temperatures.** *Radio Eng. & Electron.* **2**: 345–347, 1957.

Translation of Russian article in Radioelek. i Elektron. Describes method and results of an experimental investigation of thermo-emf near Curie point for nickel–zinc ferrites. Anomalies in Peltier and Thomson effects were found. It is shown that in some semiconductors carrier electrons take part in ferromagnetism.

1059. VAN OOIJEN, D.J. **Thermoelectric power of cold-worked platinum between liquid-air and room temperature.** *Appl. Sci. Res.* **5B**: 442–444, 1956.

Study in which 300-micron diameter platinum wires were vacuum annealed at 900°C and drawn through dies at room temperature, after drawing they were annealed at 100°C; thermoelectric force of deformed wires against undeformed wire was measured as function of hot junction temperature, with cold junction in liquid air; analysis of results.

1060. VAN OOIJEN, D. J. **The thermoelectric power of copper, silver and gold after coldworking.** 126 p., Delft, Holland, Uitgeverij Excelsior, 1957. Thesis, University of Delft, 1956.

Reports experiments on the change of the absolute thermoelectric power due to coldwork and increase of electrical resistivity.

The thermoelectric power of Cu, Ag, and Au wires, which had been cold worked by drawing at room temperature was measured against undeformed wires of the same material from liquid-thermoelectric power and of the resistivity was then followed through the recovery process brought about by slow annealing at various temperatures up to 100°C. The theory of the thermoelectric effects appropriate to the experiments is extended to cover the experimental conditions, and two independent electron-scattering mechanisms are considered.

1061. VARCHENYA, S. A. and DORFMAN, Y. G. **Thermoelectric properties of ferrites in the range close to Curie temperature.** *Radioyekh. i Elektr.* **2**: 345–347, Mar. 1957.

In Russian.

Translation in *Radio Eng.* and *Electron. (USSR).* **2**: 122–125, 1957.

Ni-Zn ferrites with specific resistance 10^6-10^7 Ωcm were examined. The Peltier and Thomson effects showed similar magnetic anomalies as found in ferromagnetic metals.

1062. VASENIN, F. I. and KONOVALOV, P. F. **Ionisation X-ray structure investigation of bismuth telluride.** *Soviet Phys. Tech. Phys.* **1**: 1376–1833, Jly. 1956.

English translation of Russian article appearing in *Zhurn. Tekh. Fiz.* **26**: 1406–1414, Jly. 1956. (See item 1525).

1063. VASENIN, F. I. **Thermoelectric properties of antimony-tellurium alloys.** *Zhurn. Tekh. Fiz.* **25**: 1190–1197, 1955.

In Russian.

The following results are tabulated in detail: (1) The electrical conductivity (σ) and thermo-emf (α) were measured for 6 samples of Sb from various sources, each containing impurities (Fe, As, Cu, Pb, Co, Ni, S, Na, Au) measured to Ω 10^{-3}0/0. The best Sb available, and that which was used for the other experiments, had σ = 26,000 Ω^{-1}. cm.^{1} and α = 31·6 μ V/°C. The Te showed on analysis traces only of Se. (2) Values of σ and α are tabulated for 24 Sb-Te alloys with compn. between 1 and 100% Sb, prepared in 3 ways: cast, compressed from powder, annealed. Results (summarised below) are compared with results by Haken (*Ann. Physik.* **4**: 312, 1910). (3) σ and α were measured for a further range of

samples with compn. close to Sb_2Te_3. Findings are that: (a) with increasing free-Te content, α falls slowly towards compn. Sb_2Te_3, dropping very sharply in the immediate neighbourhood of the stoichiometric compn.; meanwhile σ increases steadily with no tendency to show a max. (both in contradiction with Haken's results on impure materials). (b) the methods of powder met. make possible the development of homogeneous Sb-Te alloys having higher values of σ and α (c) Sb-Te alloys made from pure materials acquire increased values of α and slightly lower valuse of σ on annealing at 400° C. The quantity α^2 remains constant. (d) Addition of Pb lowers α and raises σ, both for pure Sb and for Sb-Te alloys. (e) On heating the alloys in air, oxidation begins at ~ 270° C. (f) The melting point of Sb_2Te_3 is 612° C.

1064. VASENIN, F. I. **Thermoelectric properties of systems containing bismuth-tellurium alloys.** *Zhurn. Tekh. Fiz.* **25**: 397–401, 1955.

In Russian.

Translation available from M. Friedman.

Some forty alloys were prepared. Pressed samples were also used and annealed. The compound Bi_2Te_3 is p-type with a thermoelectric power of 210 microvolt/C. Excess Te produces n-type samples, which are influenced by annealing, maximum thermoelectric conductivity is rather high, about 300 to 470 $ohm^{-1}cm^{-1}$ for the compound, and around 1000 for the n-type alloy, depending upon annealing.

1065. VENGEL', T. N. and KOLOMIETS, B. T. **Vitreous semiconductors.** *Zhurn. Tekh. Fiz.* **27**: 2484–2491, Nov. 1957.

In Russian.

Eleven compounds in the system As_2Se_3-As_2Te_3 have been investigated, and their photoelectric and thermoelectric properties are examined in relation to their chemical composition.

1066. VIDAL, D. and BLET, GEORGES. **Study of the effect of time on reheating on the thermoelectric power of polycrystalline selenium.** *Acad. Sci. Paris. Compt. Rend.* **247**: 2109–2110, Dec. 10, 1958.

In French.

For 99·995% purity the thermoelectric power decreases slightly for tempering times of about 1 hr and then stays constant independent of further heat treatment. For 99% purity the thermoelectric power decreases approximately exponentially with increasing time of heat treatment, and tends to a value characteristic of the purer material.

1067. VLASOVA, M. and STIL'BANS, L. **Thermoelectric properties of Bi-Te.** *Zhurn. Tekh. Fiz.* **25**: 569–576, 1955.

In Russian.

Report of an extensive investigation of the dependence of the thermo-emf, electrical conductivity, concentration and mobility of current carrier of Bi_2Te_3 on temperature and on departure from stoichiometric composition.

1068. VOLGER, J. **Further experimental investigations on some ferromagnetic oxidic compounds of manganese with perovskite structure.** *Physica.* **20**: 49–66, Feb. 1954.

Polycrystalline substances of the type $La_{1-\delta}Sr_{\sigma}MnO_3$ were investigated. These are ferromagnetic semiconductors which exhibit some remarkable second-order effects related to the electrical conductivity. The Seebeck effect of various samples is roughly in agreement with certain basic ideas on conductivity in oxidic semiconductors. From Hall effect measurements no conclusions could be drawn except that the apparent electron mobility is extremely small.

1069. VOLGER, J. **Some properties of (La, Sr) MnO_3.** *In* Semiconducting Materials, p. 162-171, London, Butterworths Scientific Publ. 1951.

"As an example of the controlled-valency principle semiconducting 'manganites' in the form of polycrystalline products had been prepared by Jonker and van Santen. They also found that there exists a close relation between the resistivity p and ferromagnetism, the slope of the log p vI/T curve showing an anomaly at the Curie temperature. In a certain composition range, a positive temperature coefficient of p, of the same order as for metals, was found even below this temperature. More details on the conductive properties of the compounds are given, i.e. results on the frequency dependence of p, its dependence on voltage and applied magnetic field, and results concerning the Hall-effect and the thermoelectric force. The bulk conductivity and second-order effects will be discussed." *Sci. Abs.* **54A**: 7866, 1951.

1070. WATANABE, H. and TSUYA, N. **On the properties of chromium sulphides and iron sulphides.** *Tohoku Univ. Res. Inst. Sci. Rpt.* **2A**: 503–506, June 1950.

Cr and Fe sulphides were prepared by sintering and their magnetic behaviour, electrical conductivity and thermoelectric power, vs. temperature were studied. The experimental results were checked by natural pyrrhotite; these substances are more like metals than semiconductors. Their band picture as proposed by Hirone and Miyahara should be modified by assuming that the conduction band overlaps the bands responsible for ferromagnetism.

1071. WEINRICH, O. A. and DANFORTH, W. E. **Electrical conduction and thermoelectric power in thorium oxide crystals.** *Phys. Rev.* **91**: 231, Jly. 1, 1953.

Abstract only.

"Homogeneous crystalline specimens of thorium oxide were measured in different gas atmospheres and in vacuum. In all cases where a change is made from an oxygen atmosphere to a nonoxygen atmosphere (or vacuum) the conductivity decreases. One, therefore, speculates that the material is a p-type conductor when in oxygen and in the temperature range concerned (700°–1000° C)."

1072. WEISS, H. **Determination of the effective masses in InSb and InAs by measurement of the differential thermoelectric force.** *Z. Naturforsch.* **11a**: 131–138, Feb. 1956.

In German.

Results of measurements on three p-type and five n-type specimens of InAs and on two specimens of p-type InSb indicate the following values: for InAs in the temperature range 500–800°K, $m_n = 0{\cdot}064\ m_o$, $m_p = 0{\cdot}33\ m_o$; for InSb at 333°K, $m_n = 0{\cdot}037\ m_o$, $m_p = 0{\cdot}18\ m_o$. The effective electron mass in InSv increases with temperature and reaches $0{\cdot}05\ m_o$ just below the melting point.

1073. WEISS, H. **Thermospannung und waermeleitung von III-V-berbindungen und ihren mischkristallen. (Thermoelectric power and heat conduction of III-V compounds and their mixed crystals).** *Ann. Physik.* **4**: 121–131, Jly. 21, 1959.

In German.

For III-V compounds there is a relation between the thermal conductivity and reciprocal thermal expansion coefficient. While the thermal conductivity of mixed crystals In (As_yP_{1-y}) shows a minimum value for $y = 0{\cdot}5$, the electron mobility decreases monotonically from InAs to InP. At the same time electron and hole effective masses increase. This suggests that the mean free path of electrons is at least an order of magnitude greater han that for phonons.

1074. WELKER, H. and WEISS, H. **Semiconductor compounds of predominantly homopolar character.** *Z. Metallk.* **49**: 563–570, Nov. 1958.

In German.

Predominantly homopolar semiconductors are considered and the pronounced rectifier and transistor effects, as well as thermoelectric and photoelectric effects, exhibited by compounds such as InSb are discussed.

1075. WERNICK, J. H. and WOLFE, R. **Three-element semiconductor materials.** *Electron.* **33**: 103–108, illus., Feb. 12, 1960.

Certain rules make it possible to predict new compounds. By way of summary and illustration, the prediction and investigation of the new ternary compound silver antimony telluride is described. Measurements of thermoelectric power were the first indication that $AgSbTe_2$ is a semiconductor. It is potentially useful for thermoelectric refrigeration and for power generation at moderate temperatures.

1076. Westinghouse Research Laboratories, Pittsburgh, Pa. **A study of several systems of the type Li_x $[Co_y$ $Ni_{(1-y)}]$ $(1-x)^0$** by W. D. JOHNSTON and R. C. MILLER. 19 p., May 12, 1958. (*Sci. Paper.* 431FD270-P2).

Limited availability.

Lithium substituted transition metal oxides may be of use as thermoelectric materials. In order to gain additional information as to the nature of the electrical conductivity process of these materials, the systems Li_x $[Co_yNi_{(1-y)}]_{(1-x)^0}$, $Li_x[Co_yMn_{(1-y)}]_{(1-x)^0}$ and Li_x $[Ni_yZn_{(1-y)}]$ $(1-x)^0$ have been studied. This paper deals with the preparation and crystallographic studied of these materials.

1077. Westinghouse Research Laboratories, Pittsburgh, Pa. **Methods and apparatus for measuring the figure of merit of thermoelements,** by J. A. CYPHERS. 21 p., illus., Nov. 24, 1958. (Res. Rpt. 8–1529–R23).

Limited availability.

Two steady-state methods for measuring the figure of merit of thermoelectric materials have been investigated in the course of testing a new designed measuring apparatus. One of these is the well-known $-\triangle T$ method. The other, which is initially proposed herein, is a more rapid method to employ and is based on a principle differing from that used in the maximum $-\triangle T$ method. Results obtained by both methods are presented and compared.

This report is a part of Westinghouse Thermoelectricity Progress Report 12 dated January 1959.

1078. Westinghouse Research Laboratories, Pittsburgh, Pa. **Thermoelectricity.** 11 p., illus., Mar. 17, 1958. (Prog. Rept. 2). (Contract Nobs–72361). (AD–213–743).

Materials research is proceeding in two areas: (1) mixed valency, and (2) semiconductors and semi-metals. In addition, a strong programme is being set up to grow single crystals of some of the more promising and important materials. It is apparent that single crystal measurements are necessary in order to properly evaluate a material, although the final thermoelement may be polycrystalline.

1079. Westinghouse Research Laboratories, Pittsburgh, Pa. **Thermoelectricity.** 26 p., illus., Apr. 14, 1958. (Prog. Rept. 3). (Contract Nobs–72361). (AD–215–961).

A survey is made of the properties and preparation of materials pertinent to power generation and refrigeration by thermoelectric means. Mixed valence materials are analyzed by the investigation of $Li_xMn_{1-x}O$. Ferromagnetism did not set in within the solubility range ($0 < x < 0{\cdot}35$). Further investigation revealed that this material remained semiconducting over the whole range of Li concentration. Results were consistent to the extent that ferromagnetism and metallic type conductivity did not occur. In the systems studied with (Li > 1%), it is believed that the carriers are all essentially free from the Li+ at room temperature and that the measured activation energy is mainly for mobility and not carrier formation. Two experiments are considered on the present model of charge carrier mobility. A free energy of activation for mobility of the order of 10 kcal is indicated. The activation energy for conductivity is of the same order, so that the holes appear essentially free

at the temperature of the experiment. Some of the considerations for a mixed valence material having a high figure of merit are (1) heavy elements, (2) low crystallographic symmetry, (3) a large number of atoms/cell, (4) small mass doping constituents, and (5) controlled cation-anion overlap.

1080. Westinghouse Research Laboratories, Pittsburgh, Pa. **Thermal electrical power. I. General theory,** by CLARENCE ZENER. 7 p., Aug. 11, 1952. (Res. Rept. R–94460–2–0).

Purpose of this report is to evaluate the potentialities of obtaining electric power directly from a temperature difference, and to indicate along which directions one should search for better thermoelectric materials. In Section I the formal theory is reviewed, the efficiency of the thermoelectric system being obtained in terms of certain material parameters. It is found that even for the best materials known at present, the efficiency of a thermoelectric system is very low, at the order of magnitude of 3 percent. In Section II an analysis is made of those characteristics of the detailed structure of a material which influences this efficiency, and suggestions are made as to which materials show promise of a marked increase in efficiency. It is concluded that a certain class of materials, of the type of FeS, promise a sufficiently high efficiency as to warrant an experimental investigation.

1081. Westinghouse Electric Corp., Pittsburgh, Pa. **Thermoelectric nuclear fuel element,** by F. F. L. CARTER *et al.*, 72 p., Feb. 13, 1959. (Quart. Prog. Rept. 2). (Contract At(30–3)–500).

A new class of potential thermoelectric materials the pervoskites, has been included under material investigation. Work has been initiated on $La_xBa_{1-x}TiO_3$, $Y_xCa_{1-x}TiO_3$, and $Al_xMg_{1-x}TiO_3$, all of which are n-type materials. Work has also been begun on a p-type pervoskite, $Ca_xY_{1-x}UO_3$. Studies were continued on CeS_x and $CeSe_x$ type materials. Compounds of the composition $Ce(S^{-2}Se^{-2})_x$, where $1{\cdot}33 < x < 1{\cdot}50$ were prepared. Thermoelectric property measurements on $Li_x(Mg_yNi_{1-y})_{1-x}O$ materials revealed the electrical resistivities of these materials to be too high to make them practical. Some room-temperature measurements were made on the CeS_x and $Ce(S,Se)_y$ materials. The thermoelectric measurements on $La_xBa_{1-x}TiO_3$ show that an efficiency of over 2% can be obtained at 400°C, and extrapolated data indicate that 6% should be possible at 1000°C. The use of UO_2 as a thermoelectric material does not appear too attractive. Bonding studies were continued on $Li_xNi_{1-x}O$ type materials. Experiments on $Li_xNi_{1-x}O$-ceramic couples indicated that ZrO_2, Al_2O_x, and MgO showed no reaction up to 1100°C, but SiO_2 forms a low-melting phase below this temperature.

1082. Westinghouse Electric Corp., Pittsburgh, Pa. **Thermoelectric nuclear fuel element.** Annual Progress Report, by J. C. DANKO *et al.* 111 p., April 15, 1959. (Rept. WCAP–1162). (Contract AT(30–3)–500).

Reviews thermoelectric design considerations, preparation and thermoelectric properties of mixed valence materials; irradiation; fabrication; physical and chemical properties of thermoelectric materials; bonding and insulator studies; and measuring apparatus.

1083. Westinghouse Electric Corp., Pittsburgh, Pa. **Thermoelectric nuclear fuel element.** 29 p., Jan. 10, 1960. (Quart. Prog. Rept. 3). (WCAP–1376).

Thermoelectric materials were prepared for irradiation studies and fabrication studies. Techniques were developed for the preparation of some uranium-bearing thermoelectric materials. Conclusions are listed concerning determination of the thermoelectric and physical properties of swaged GeTe and PbTe.

1084. WHITE, G. K. and WOODS, S. B. **Electrical and thermal magneto-resistance in thin rods of pure sodium.** *Phil. Mag.* **1**: 846–853, Sept. 1956.

Measurements are reported on the resistivity of 130 and 350μ diameter rods of high purity sodium in transverse magnetic fields (1 to 10,000 oersteds) and at temperatures between 2 and 18°K.

1085. WHITE, G. K. and WOODS, S. B. **Thermal and electrical conductivity of rhodium, iridium, and platinum.** *Can. J. Phys.* **35**: 248–257, Mar. 1957.

Rapid rate of decrease of "ideal" thermal and electrical resistivities with temperature, particularly in Rh and Ir, suggests that s-d transitions are not dominant resistive mechanism at low temperatures in these metals, in contrast to Pd, Fe and Ni.

Includes 20 references.

1086. WHITE, G. K. and WOODS, S. B. **Thermal and electrical conductivities of solids at low temperatures.** *Can. J. Phys.* **33**: 58–73, figs., 1955.

An apparatus for measuring the thermal and electrical conductivities of solids at temperatures between 2° and 300°K is described. Results are presented of measurements of some dilute copper alloys, beryllium, bismuth, and germanium. Where possible the lattice thermal conductivity has been deduced, directly or indirectly from the measurements, and its magnitude and variation with temperature are discussed with relation to theory.

1087. WHITE, G. K. and WOODS, S. B. **The thermal and electrical resistivity of bismuth and antimony at low temperatures.** *Phil. Mag.* **3**: 342–349, Apr. 1958.

Measurements are reported of the electrical resistivity of pure polycrystalline specimens of bismuth and antimony over the range 2° to 300°K and of the thermal conductivity up to 150°K. Some measurements in a magnetic field have also been made which allow separation of the thermal conductivity into electronic and lattice components. Below 50°K, it appears that the heat conductivity

of bismuth is nearly all due to lattice waves; free electrons seem to contribute little to the conduction or to the scattering. In antimony, however, the lattice conductivity is smaller than might be expected at low temperatures suggesting significant scattering by free electrons.

1088. WHITE, W. C. **Some experiments with Peltier effect.** *Elec. Eng.* **70**: 589–591, Jly. 1951.

Experiments have been made on new alloys to determine the practicability of using the Peltier effect in a thermoelectric power generator.

1089. WILLARDSON, R. K., BEER, A. C. and MIDDLETON, A. E. **Electrical properties of semiconducting AlSb.** *Electrochem. Soc. J.* **101**: 354–358, 1954.

Experimental investigations of the resistivity, thermoelectric power, and Hall coefficient over the temperature range 80° to 1200°K were made. The energy band separation is 1·5–1·6 eV; electron and hole mobilities are approximately equal and are over 100 cm²/volt-sec. Rectification has been observed for both p-type and n-type specimens. The semi-conducting characteristics are similar to those of Si.

1090. WILLARDSON, R. K. **New semiconductor materials.** *Battelle Tech. Rev.* **6**: 8–14, illus., Aug. 1957. Thermoelectric materials, p. 13–14.

1091. WILLIAMS, W. **Some adiabatic and isothermal effects in bismuth telluride.** *Phys. Soc. Proc.* **73**: 739–744, figs., May 1, 1959.

Isothermal and quasi-adiabatic Hall and Nernst coefficient were measured on n- and p-type Bi_2Te_3 over a temperature range 100°K to about 450°K with the magnetic field either parallel or perpendicular to the cleavage planes. The difference between the two Hall coefficients follows the expected variation with temperature. However, the Nernst coefficients do not, and the reason is not known. Results obtained with the magnetic field perpendicular to the cleavage planes have been used to calculate the Ettinghausen effect.

1092. WINKLER, U. E. **The electrical properties of the intermetallic compounds Mg_2Si, Mg_2Ge, Mg_2Sn, and Mg_2Pb.** Dissertation, E.T.H. Zurich, No. 2501, 633–666, 1955.

In German.

"Gives detailed results of measurements of the electrical conductivity, the Hall effect, and the thermoelectric effect on polycrystalline specimens of these intermetallic compounds prepared by direct melting. Measurements were made over the temperature range 100–1100°K and the results show that Mg_2Si, Mg_2Ge, and Mg_2Sn behave as true semiconductors while the results for Mg_2Pb indicate that this compound is a strongly degenerate semiconductor. Particulars of the electrical constants of these compounds are given." *Sci. Abs.* **60A**: 5334, 1957.

1093. WORNER, H. W. **Thermoelectric properties of titanium with special reference to the allotropic transformation.** *Australian J. Sci. Res.* **4A**: 62–83, Mar. 1951.

A differential method for determining the thermoelectric power of Ti/Pt thermocouples is described. The results are compared with data obtained in direct emf temperature determinations. The temperature-dependence of the following has been deduced: (*a*) the Peltier coefficient of the Ti-Pt couple; (*b*) the difference between the Thomson coefficients of Ti and Pt; (*c*) the absolute thermoelectric power of Ti. It is shown that abrupt changes in thermoelectric properties accompany the α-B transformation in refined Ti, the transition temperature range being 883 ± 1 to 867 ± 2°C. In a commercial grade the transformation occurs over the range 865° to 970°C. Some effects due to preferred orientation and the elimination thereof are also reported.

1094. WRIGHT, D. A. **Bismuth telluride and related compounds.** *Res.* **12**: 300–306; Aug./Sept., 1959.

This article summarizes the present knowledge. Particular attention is paid to those properties which have a bearing on thermoelectric performance.

1095. WRIGHT, D. A. **Some physical properties of bismuth telluride.** *In* Semiconductors and Phosphors, Proceedings of International Colloquiem held in Garmisch-Partenkirchen, 1956, p. 477–481, Brunswick, Vieweg, 1958.

Not examined.

This paper summarizes information on the crystal structure, preparation, electrical and thermal conductivity, Hall effect, thermoelectric power and band structure of Bi_2Te_3.

1096. WRIGHT, R. W. and ANDREWS, J. P. **Temperature variation of the electrical properties of nickel oxide.** *Phys. Soc. Proc.* **62A**: 446–455, Jly. 1949.

An experimental method of preparing specimens of NiO in the form of coherent strips is described. Simultaneous measurements of electrical conductivity and Hall effect are then made at various temperatures up to about 700°C and the thermoelectric power measured immediately afterwards, all on one sample. NiO behaves like a defect semiconductor, "hole" conductivity predominating. The significance of these results is discussed.

1097. WRIGHT, D. A. **Thermoelectric properties of bismuth telluride and its alloys.** *Nature* **181**: 834, Mar. 22, 1958.

Progress since 1954 in the production of pure p- and n-type Bi_2Te_3 is reported. A maximum temperature difference of 65°C, at a mean temperature of 17°C, and Hall electron mobilities as high as 300 cm²/Vsec have been obtained with these materials, and a maximum temperature difference of 80°C at the same mean temperature has been obtained by combinations of alloys of analogous materials.

1098. WRIGHT, D. A. **Thermoelectric properties of semiconductors.** *Electron.* **32**: 70–71, table, June 19, 1959.

Important semiconductors are evaluated for thermoelectric performance. Figures of merit, presented for each material, place bismuth telluride and lead telluride at top of list; ten well-known semiconductors are presented in a convenient table that shows their comparative characteristics.

1099. WRIGHT, R. W. **The variation with temperature of the electrical properties of a degenerate electronic semiconductor as exemplified by cadmium oxide.** *Phys. Soc. Proc.* **64A**: 350–362, Apr. 1951.

Simultaneous measurements of the Hall constant R and the electrical conductivity were made throughout the temperature range 0–500°C, and the thermoelectric power dE/dT was measured immediately afterwards for each specimen. The properties were found to resemble those of a metal. The theory of degenerate semiconductors is developed, and since the values of R indicate that there is a constant number of free electrons in each specimen, this result is incorporated into the comparison of the theory with the experimental results. The approximate form of the theory predicts that the thermoelectric power and the resistivity should be directly proportional to the absolute temperature; the experimental results are found to confirm this.

1100. WRIGHT, R. W. and BASTIN, J. A. **The characteristic temperature and effective electron mass for conduction processes in cadmium oxide.** *Phys. Soc. Prco.* **71B**: 109–116, Jan. 1958.

Measurements of the Hall effect, resistance, magnetoresistive effect, and thermoelectric power were made for over 50 specimens prepared by sintering compressed powder blocks of CdO.

1101. WRIGHT, H. C. and BRICE, J. C. **Indium monotelluride.** *Nature* **183**: 27–28, Jan. 3, 1959.

A report of measurements which reveal the anomalous properties of the compound. Certain electrical properties indicate a metallic nature, but the large value of the thermal emf, the computed Wiedemann–Franz ratio and the large variation of resistivity are more characteristic of a semiconductor.

1102. WRIGHT, R. W. **Variation with temperature of electrical properties of degenerate electronic semiconductor as exemplified by cadmium oxide.** *Phys. Soc. Proc.* **64B**: 350–362, Apr. 1, 1951.

Measurement of Hall constant, specific conductivity, thermoelectric power, and their variations with temperature, on same sintered specimen of cadmium oxide; development of theory of degenerate semi-conductors.

1103. YABUMOTO, TADAICHI. **Electrical and optical properties of germanium sulfide.** *Phys. Soc. Japan. J.* **13**: 559–562, 1958.

Samples were prepared by heating stoichiometric quantities of Ge and S in evacuated quartz ampules at 800° and then homogenizing at 1050° for 6 hours. The samples were then sublimed in NH_3. The thermal activation energy for the dark current was 0·74 eV for high temperatures and 0·24 to 0·5 eV for low temperatures.

1104. YADAV, Ram. **Antimony-zinc alloy with thermoelectric properties.** *Indian Patent No.* 50, 761, Nov. 24, 1955.

The alloy is prepared from Zn 25, Sb 65, and Ag or Cu 0·2–1·0%.

1105. YAMAKA, E. and SAWAMOTO, K. **Electrical conductivity and thermoelectromotive force in MgO single crystal.** *Phys. Soc. Japan. J.* **10**: 176–179, Mar. 1955.

Electrical conductivities of MgO single crystals were measured by an a.c. method from 650°C to 1000°C. Curves of log σ_v 1/T have the slope of 2·3 eV Specific resistivities of magnesium-coloured samples are smaller than those of uncoloured and oxygen-coloured samples, so that it may be concluded that charge carriers originate from impurity levels of oxygen vacancies or interstitial magnesium atoms. The measurements of sign of thermoelectric motive force showed that charge carriers are electrons in all samples. The values of Te are from 0·1 mV deg to 10 mV/deg at various concentrations of excess magnesium.

1106. YATES, B. **The electrical conductivity and hall coefficient of bismuth telluride.** *J. Electron. & Contr.* **6**: 26–38, Jan. 1959.

Describes the variation of the electrical conductivity and Hall coefficient of a number of specimens of Bi_2Te_3 over a wide range of doping concentrations. A detailed examination of these quantities, over the temperature range 1·3 to 660°K, has revealed the existence of trends which vary systematically with the degree of doping, although anomalies exist within this scheme. It is shown that an impurity band mechanism may operate in n-type Bi_2Te_3.

1107. YOCKEY, H. P. **Use of thermocouples in a radiation field.** *Phys. Rev.* **101**: 1426, Feb. 15, 1956.

Discussion of experimental work on the effect of radiation damage on the thermoelectric power of metals.

1108. YOKOYAMA, TOHRU. **Experimental studies on the formation of superlattice in FeCo alloys. IV. Thermoelectric motive force, thermal expansion and X-ray investigation.** *Nippon Kinzoku Gakkai-Si* **21**: 321–324, 1957.

In Japanese.

"The variation of thermo-emf, thermal expansion, and the lattice construction with temperature in FeCo alloys is discussed and illustrated graphically. When ordered specimens are heated from room temperature, the thermo-emf falls sharply at 550°C and then gradually from 550° to 730°C. The thermal expansion coefficient reaches

a maximum at 730°C, falls with temperature, but increases slightly again at 550°C. These results are correlated with a high-temp. X-ray study, which shows that the lattice const. changes markedly at 550° and 730°C." *Met. Abs.* 910, Aug. 1958.

1109. YOUNG, J. R. **Electrical conductivity and thermoelectric power of (BaSr)O and BaO.** *J. App. Phys.* **23**: 1129–1138, Oct. 1952.

A study was made of thermoelectric power, electrical conductivity, and thermionic emission on BaO and (BaSr)O oxide-coated cathodes showed results not explainable by simple semiconductor theory but in good agreement with the pore-conduction hypothesis.

1110. ZHUZE, V. P., TSIDIL'KOVSKY, I. M. and BARTNITSKAYA, T. S. **Thermomagnetic phenomena in silver telluride.** *Zhurn. Tekh. Fiz.* **28**: 1646–1650, Aug. 1958.

In Russian.

Measurements were made (120–600°K) of the longitudinal and transverse Nernst-Ettinghausen fields, the termo-emf, Hall constant and conductivity of Ag_2Te and AgTe. The results are analyzed in several temperature intervals. Earlier suppositions that the bonding in Ag_2Te changes from covalent-metallic to ionic in the phase change at 150°C are confirmed; the bonding in AgTe was ionic throughout the temperature range used. (*Metall. Abs.* **26**: 465, Feb. 1959.)

1111. YURKOV, V. A. **Physical properties of lead-antimony alloys.** *Akad. Nauk. SSSR. Dok.* **91**: 891–893, 1953.

In Russian.

The values of the linear expansion, d., electrical resistance, and thermal emf were determined for Pb-Sb alloys in relation to their composition. The eutectic occurs at a composition of 13% Sb (melting point=247°).

1112. YURKOV, V. A. and ALEKSEEVA, N. E. **Thermoelectric properties of Cd-Sb alloys.** *Zhurn. Tekh. Fiz.* **26**: 911–912, Apr. 1956.

In Russian.

The variation of thermoelectric power with composition was studied. A very sharp maximum (285μV/deg C) was found at the composition CdSb. A secondary maximum appeared to be associated with the (metastable) compound Cd_3Sb_2.

1113. YURKOV, V. A. and NEKRASOV, V. V. **Thermoelectrical properties of the alloys tin-cadmium and lead-cadmium.** *Fiz. Metal. i Metalloved.* **8**: 21–24, 1959.

In Russian.

For brief English abstract see *Chem. Abs.* **54**: 5403, Mar. 25, 1960.

1114. ZHUZE, V. P. and REGEL', A. R. **Electrical properties of alloys of the systems NiTe-$NiTe_2$.** *Zhurn. Tekh. Fiz.* **25**: 978–983, 1955.

In Russian.

Homogeneous specimens were obtained by direct fusion with subsequent prolonged annealing, or by sintering under pressure. Maxima in thermal and electrical conductivity, and minima in thermoelectric power were observed at NiTe and $NiTe_2$. The temperature coefficient of resistivity in the range 20–300°C was always metallic. It was concluded that bonding in the system was predominantly metallic though measurements on NiTe single crystals might show it to have semiconducting properties. Preliminary measurements on $CoTe_2$ showed that it resembled $NiTe_2$.

1115. ZHUZE, V. P., SERGEEVA, V. M. and SHTRUM, E. L. **New semiconducting compounds.** *Zhurn. Tekh. Fiz.* **28**: 233–236, 1958.

In Russian.

Electrical conductivity, thermoelectric power, Hall effect, crystal structure, melting point and micro-hardness were studied for $A'FeX_2^{VI}$ compounds (A'=Cu, Ag; X^{VI}=S,Se,Te), in particular $AgFeSe_2$ and $AgFeTe_2$. The latter had tetragonal structures, which were not of chalcopyrite type (though probably related to it). An electronic mobility greater than 2000 cm^2V^{-1} sec^{-1} was obtained with polycrystalline $AgFeTe_2$ (~500 ohm^2. cm^{-1}). Evidence suggested a phase transformation in this compound at ~145°C included a marked change in volume.

1116. ZHUZE, V. P., SERGEEVA, V. M. and SHTRUM, E. L. **Semiconducting compounds with a general formula ABX_2.** *Zhurn. Tekh. Fiz.* **28**: 2093–2108, Oct. 1958.

Investigation of ternary compounds which crystallize in the chalcopyrite ($CuFeS_2$) pattern and which were first synthesized in 1953 by Hahn. Data are given on new compounds some of which crystallize in tetragonal systems. All these compounds proved to be semiconductors.

1117. ZIMAN, J. M. **The electrical and thermal conductivities of monovalent metals.** *Roy. Soc. London. Proc.* **226A**: 436–454, illus., 1954.

The scattering of electrons by the thermal lattice vibrations is considered. The original Block theory is qualitatively in agreement with experiment, but has been shown by various authors to be unrealistic in its detailed assumptions. In particular, it ignores Umklapp processes, neglects the difference between longitudinal and transverse phonon velocities, and treats electron-phonon interaction as if it were independent of the scattering angle.

1118. ZUEV, K. P. **Thermo-emf of cuprous oxide at high temperatures (1000° to 1250°C). IV.** *Soviet Phys. Solid State* **1**: 1007–1015, Jan. 1960.

"In this paper, the thermo-emf of Cu_2O is investigated for the first time in the temperature interval from 1000° to 1250°C, and as a function of changes in the oxygen pressure of the surrounding medium over a wide interval (p_{O2}=1 to 760 mm Hg). It is shown that the absolute value of the thermo-emf in Cu_2O increases continuously with heating and it achieves its maximum value at the temperature which corresponds to the transition of

the sample through the boundary of the stability of Cu_2O-CoO; then it falls rapidly reaching 250μv/deg at the melting temperature of Cu_2O (1235°C).

The transformation of Cu_2O from the solid to the liquid phase is studied. The data again confirm the idea that shortrange order plays a decisive role.

A definite relation between the curves of the dependence of the thermo-emf of Cu_2O on composition near the boundary of the stability region of Cu_2O and CuO is shown to exist, and this boundary can be accurately located by means of the experimental data. A correlation between the temperature dependence of the thermo-emf and of the electrical conductivity at high temperatures (1000° to 1250°C) is established.

The results of the investigation are successively compared and analyzed, starting from the conditions of thermodynamic equilibrium in the Cu-O_2 system."

MATERIALS

(Measurements)

1119. ABELES, B. **Thermal conductivity of germanium in the temperature range 300°–1080°K.** *Phys. & Chem. Solids* **8**: 340–343, 1959.

Simultaneous measurements of the thermoelectric power and electrical conductivity are reported and experimental methods are detailed.

1120. Armour Research Foundation, Chicago, Ill. **Methods for measuring thermal conductivity** 23 p., n.d.

Methods for measuring thermal conductivity of materials are described for the purpose of indicating methodology for selecting and evaluating materials for possible use in thermoelectric generators.

1121. BARANSKII, P. I. and LASHKAREV, V. E. **The measurement of volume thermal emf in germanium.** *Zhurn. Tekh. Fiz.* **27**: 1161–1166, June 1957.

In Russian. Translation in *Soviet Phys. Tech. Phys.* **2**: 1055–1060, June 1957.

"An analysis of the basic errors which arise in the study of the thermal electromotive forces in n- and p-germanium when pressure contacts are utilized. Proposals are made for eliminating these errors. It is shown that in properly conducted experiments the relationship $\alpha=\alpha(\triangle T)$ does not show up." *Electron. Exp.* **1**: 15, Mar. 1958.

1122. Battelle Memorial Institute, Columbus, Ohio. **Measurement of thermal conductivity by utilization of the peltier effect,** by T. C. HARMON, J. H. CAHN and M. J. LOGAN. 9 p., illus., Dec. 31, 1958. (Tech. Rept. 2) (Contract Nonr–231–600). (AD–228–784).

Reprint from *J. Appl. Phys.* **30**: 1351–1359, Sept. 1959. For original entry see Item 1228 March 1960 issue.

1123. Battelle Memorial Institute, Columbus, Ohio. **Special measurement techniques for thermoelectric materials with results for Bi_2Te_3 and alloys with Bi_2Se_3,** by T. C. HARMAN and M. J. LOGAN. 17 p., June 1, 1958. (Tech. Rept. 1). (Contract No.–2316(00)). (AD–201–111).

A new technique devised for accurate measurement of the absolute values of thermoelectric power and thermal conductivity involves use of the Peltier heat to maintain a temperature gradient across the specimen. Measurement of this gradient, the voltage across the specimen, and the a.c. resistivity allows calculation of the absolute values of the thermoelectric power and thermal conductivity. The thermoelectric figure of merit is given in terms of the ratio of voltages.

1124. BOLTAKS, B. I. **Dependence of the coefficient of the thermo-emf in semiconductors on the temperature difference of the junctions (on Henisch's, Schweikert's and Rode's papers).** *Zhurn. Tekh. Fiz.* **20**: 1039–1048, Sept. 1950.

In Russian.

The measurements carried out on TiO_2 and Cu_2O at various temperature differences of the junctions showed that the Henisch effect for TiO_2 and the dependence of α on $|T_1-T_2|$ for Cu_2O have nothing to do with the characteristics of the substances, but are due to experimental shortcomings. Henisch's statement that measurements of the thermo-emf must not be used for determining the sign of the charge carriers seems to be without foundation. Greatest care has to be taken to ensure that thermocouples measure true temperature of the specimen, viz., that at the points between which thermo-emf is measured. The experimental findings agree with the Davydov and Shmushkevich theory of the thermo-emf.

1125. BOLTAKS, B. I. **The problem of measuring the thermo-emf of semiconductors.** *Zhurn. Tekh. Fiz.* **22**: 892–893, 1952.

In Russian.

Rejoinder to a note by Henisch replying to previous criticism by the author of Henisch's observations on a new effect, viz., the strong dependence of the thermo-emf on the value of the temperature difference of the junctions for the same values of the mean temperature of the specimen. Repetition of Henisch's experiments by the author proved Henisch's observations to be due to experimental errors and not to characteristics of the substances investigated. Experiments without removing the established sources of error produced the "Henisch effect"; properly conducted experiments were free of it.

1126. BRICE, J. C. and WRIGHT, H. C. **Apparatus for measurement of thermal-emf in semiconductors.** *J. Sci. Instr.* **35**: 146–147, Apr. 1958.

Since semiconductor specimens are often available only as small prisms or thin laminae, thermoelectric measurements offer problems in thermometry not encountered when the material is in the form of a wire. In order to make an accurate measurement of the temperature of their specimens Skanivi and Kashtanova have screwed thermocouples on to the specimen surface and then coated them with a water-glass or asbestos mixture. Hutson has used subsidiary heaters on his thermocouple leads to obviate a temperature gradient along them. This article described an apparatus which has been in use for some months, and which offers a very simple way of achieving a similar end.

1127. HARMAN, T. C., CAHN, J. H. and LOGAN, M. J. **Measurement of thermal conductivity by utilization of the peltier effect.** *J. Appl. Phys.* **30**: 1351–1359, Sept. 1959.

A special technique for the accurate measure-

ment of thermal conductivity is discussed. The method involves use of the Peltier heat to maintain a temperature gradient along the specimen. Straightforward measurements allow calculation of the absolute value of the thermoelectric power, thermal conductivity, and electrical resistivity. An especially useful feature of the method is that the thermoelectric figure of merit is given in terms of the ratio of two voltages. The theory is presented for the case in which the radiative heat transfer is important. The method has been tested experimentally at 300°K only, analysis suggests that accurate measurements of thermal conductivity can be made by this technique on low thermal conductivity materials of small dimensions up to 1000°K.

1128. HARMAN, T. C. **Special techniques for measurement of thermoelectric properties.** *J. Appl. Phys.* **29**: 1373–1374, Sept. 1958.

Special techniques for measuring the thermal conductivity, thermoelectric power, and the figure of merit of thermoelectric materials such as bismuth telluride are discussed. It is shown how the thermal conductivity can be calculated when the thermoelectric power, current, temperature gradient and geometry of the specimen are known. The thermoelectric power can be determined by dividing the absolute Seebeck voltage of the specimen by its temperature gradient. The figure of merit can be determined by dividing the absolute Seebeck voltage of the specimen by the product of the IR drop in it and the absolute temperature. Experimental precautions which must be taken are pointed out.

1129. HERINCKX, C. and MONFILS, A. **Electrical determination of the thermal parameters of semiconducting thermoelements.** *Brit. J. Appl. Phys.* **10**: 235–236, 1959.

Equations are developed from which the thermal conductivity, thermal capacity, and electrical conductivity can be obtained by measurement of the electric p.d. across a semiconductor due to its own thermoelectric force. The method is illustrated for BiTe.

1130. HOPKINS, M. R. **The thermal and electrical conductivities of metals at high temperatures.** *Z. Physik.* **147**: 148–160, 1957.

In German.

A method of investigating the electrical and thermal conductivities of metals at high temperatures is described. The theory of the method depends upon the application of ideas which are fundamental in the study of electrical contact phenomena. The ratio of the thermal to the electrical conductivity of platinum has been determined from 1200°C to the melting point (1773°C) and from the melting point to 2300°C by making simultaneous observations of electrical potential and maximum temperature in a short wire through which current is passed.

1131. IOFFE, A. F. **A simple method of measuring thermal conductivity.** *Zhurn. Tekh. Fiz.* **22**: 2005–2013, 1952.

In Russian.

Substance is clamped between an upper copper block A (Temp. Ta) and a lower copper block B (temp. b). Initially the whole system is at ambient temperature T_0. The lower block is then immersed in a low-temperature bath. The thermal conductivity of material between blocks A and B is obtained from measurement of the time variation of (Ta-Tb) and (Ta-T_0). Various applications of the method are outlined; (*a*) the thermal conductivity of semiconductors, (*b*) a comparison of thermal conductivity of amorphous and crystalline solids, *e.g.*, sulphur and selenium.

1132. KAGANOV, M. A., LISKER, I. S. and MUSHKIN, I. G. **Measurement of the thermoelectric properties of semiconductors.** *Fiz. Tverdogo Tela* **1**: 988–990, June 1959.

In Russian.

"A correction factor for heat loss applied to a formula of Harman (*J. Appl. Phys.* **29**: 1373–1374, Sept. 1958), is shown to be independent of the current intensity." *Electron Tech.* **37**: 1271, Apr. 1960.

1133. KORENBLIT, L. L. and SHTEINBERG, A. A. **A graphical method for determining chemical potential in semiconductors.** *Zhurn. Tekh. Fiz.* **26**: 927–937, 1956.

Trans. in *Soviet Phys. Tech. Phys.* **1**: 912–920, May 1957.

Proposes method using a glass sheet illuminated from below; transparent sheet with mm. squares is placed on the glass and also two tracings with "universal" graphs. By appropriately displacing these sheets with respect to each other, the chemical potential and its temperature dependence are determined. Method has been used for investigating electric and TE properties of semiconductors with mixed conductivities, and some results are reported.

1134. KROEBEL, W. **A method for the amplification of extremely small thermoelectric voltages.** *Z. Angew. Physik* **5**: 286–291, Aug. 1953.

In German.

Describes an amplifier for signals of order $1{\cdot}5\times10^{-9}$v at about 10 c/s and from a measuring circuit resistance of 10Ω. With modifications 10^{-10}V can be measured.

1135. LANDER, J. J. **Measurements of Thomson coefficients for metals at high temperatures and of Peltier coefficients for solid-liquid interfaces of metals.** *Phys. Rev.* **74**: 479–488, 1948.

Although the thermoelectric Peltier and Thomson effects are usually of secondary importance in practical electrothermal phenomena, they may become of immediate importance when thermal or electrical symmetry is a primary consideration. This article describes apparatus devised for measuring and measurements made of: (*a*) the

liquid-solid Peltier coefficients of Au, Ag, and Cu; and (*b*) the Thomson coefficients for solid Pt, Pd, Ag, Au, Cu, W and Mo at high temperatures.

1136. LOUGHER, E. H. **Measurement of parameters in the thermoelectric figure of merit.** *Elec. Eng.* **79**: 358–364, figs., May 1960.

Some of the more effective methods for measuring such important parameters of thermoelectric materials as Seebeck coefficient, thermal conductivity, and electrical resistivity are described.

Includes 22 references.

1137. National Bureau of Standards, Washington, D.C. **Electroluminescence and thermoelectricity,** by G. G. HARMAN and R. L. RAYBOLD. 23 p., Dec. 1, 1959. (AD229814).

Unpublished report.

A thermoelectric measuring apparatus was designed and constructed. It is capable of measuring thermoelectric power from 77°K to 1100°K in air, various ambients, and in moderate vacuum. Tentative results indicate that some high resistivity n-type SiC changes to p-type at about 500°C and would not be suitable for high-temperature devices. A more detailed study is necessary, however.

1138. National Bureau of Standards, Washington, D.C. **Thermal conductivity of semiconductive solids; method for steady-state measurements on small disc reference samples.** May 24 to Sept. 30, 1959. 4 p., Sept. 30, 1959 (TPR Index 058–001).

Progress report on a part of a major programme on the development of materials for thermoelectric power generation.

1139. National Bureau of Standards, Washington, D.C. **Thermal conductivity of semi-conductive solids; method for steady-state measurements on small disc reference samples.** Sept. 30, 1959 to Dec. 30, 1959. 5 p., Dec. 31, 1959 (TPR Index NS058–001).

Attention was concentrated on study of the two major sources of inaccuracy: (a) conduction of heat into the powder insulation surrounding the heat source, and (b) contact resistances at the specimen surfaces.

1140. New York Naval Shipyard, Material Laboratory, New York, N.Y. **A proposed method for measuring thermal diffusivity at elevated temperatures.** Final Report by A. HIRSCHMAN, W. L. DERKSEN and T. I. MONAHAN. 13 p., Apr. 30, 1959. (Project 5046-3, Pt. 119).

It is proposed to measure the thermal diffusivity of solids in the form of finite slabs by periodic irradiation of one face and comparison of the phase difference between the resulting temperature oscillations of the back face and those of the irradiated face. The purpose of this report is to describe the method, the underlying theory and experimental techniques. Some advantages and limitations are described. Design of elements for thermoelectric conversion of power from a heat source at a fixed temperature requires a knowledge of thermal conductivity; since thermal diffusivity is the ratio of thermal conductivity to volumetric specific heat, thermal conductivity can be computed from the measured diffusivity and the volumetric specific heat, whose variations with temperature can be measured with the experimental equipment described herein.

1141. Radio Corporation of America. David Sarnoff Research Center, Princeton, N.J. **Thermal and electrical properties of material,** by B. ABELES, G. D. CODY, and R. NOVAK. 33 p., Mar. 31, 1959. (Prog. Rept. 1) (Contract AF33 (616)-6165) (AD 225 854).

Research on principles causing thermoelectric behaviour and their use to control thermoelectric characteristics of material. This report deals with the GaAs-InAs system and with a method of measuring high-temperature thermal conducitvities.

1142. Radio Corp. of America. David Sarnoff Research Center, Princeton, N.J. **Thermal and electrical properties of materials.** 8 p., Jan. 15, 1960. (Quart. Prog. Rept. 4) (Contract AF33(616)-6165).

Confirmation of the previously obtained diffusivity of germanium is reported through the use of thermocouples for temperature measurements rather than the probe method previously reported. Apart from confirming the previous results, the new method should permit the extension of the diffusivity measurements to semiconductors which lack the homogeneity required for the probe techniques. An analysis of the results obtained for Armco iron is given, which relates the phenomena observed to the electrical and thermal properties of iron at elevated temperature. A brief description of the proposed specific heat measurements is given.

1143. SHTENBEK, M. and BARANSKII, P. I. **Methods for precision measurement of the Peltier effect and the thermoelectric power.** *Soviet Phys. Tech. Phys.* **1**: 1345–1359, 1957.

Translation of Russian article in *Zhurn. Tekh. Fi*$_3$. **26**: 1373–1388, 1956.

1144. SHTENBECK, M. and BARANSKII, P. I. **Methods for the precise measurement of Peltier effect and thermoelectromotive force.** *Zhurn. Tekh. Fiz.* **26**: 1373–1388, 1956.

In Russian.

If the Peltier temperature difference ($\triangle$T) between the ends of a specimen conducting a current i, is annulled by introducing thermal energy W at the cooled end, then the Peltier voltage, P = W/2i (provided that the system is perfectly symmetrical thermally and that there is no heat loss perpendicular to the specimen axis). For departures from thermal symmetry, curves of W against $\triangle$T for forward and reverse current flow intersect at W = W*, ($\neq$T = 0), and P = W*/2i. Non-ohmic behaviour in the specimen or its contacts can be eliminated by determining the variation of P with i and extrapolating to i = 0.

For an inhomogenous specimen it is found that P is averaged in the same way as is the thermoelectric power α. An apparatus applying the new method is described in detail, and errors in measurement are analysed. An accuracy of 1% for P is claimed. A simple method for the simultaneous determination of α within 1% is also described. It is noted that experiments on Ge do not confirm the validity of the Kelvin relationship $P = \alpha T$.

1145. SIDLES, P. H. and DANIELSON, G. C **Thermal diffusivity of metals at high temperatures.** *J. Appl. Phys.* **25**: 58–66, Jan. 1954.

A modified Angström method for measuring thermal diffusivity and hence thermal conductivity of metals developed. Using a heat source whose temperature varies sinusoidally with time, located at one end of an effectively infinite rod. Only one period of the heat pulse is required to eliminate the unknown coefficient determining the heat loss by radiation since both velocity and amplitude decrement of the heat pulse are measured. In addition to providing greater reliability at high temperature by using only one period, the method is faster in taking data and simpler in computation. Thermoelectric potentialities from two thermojunctions are amplified and plotted on a Brown electronic recorder. Results for Cu, Ni, and Th over the range 0·500°C are given.

1146. SKAVANI, G. I. and KASHTANOVA, A. M. **Methods of measuring the coefficient of thermo-emf in semiconductors.** *Zhurn. Tekh. Fiz.* **26**: 895–899, 1956.

In Russian.

Translation in *Soviet Phys. Tech. Phys.* **1**: 687–694, 1957.

A discussion of practical difficulties in measuring thermoelectric power is followed by a detailed description of two different types of apparatus suitable for use from room temperature up to (a) 240°C, (b) 320°C.

1147. STUCKES, A. D. and CHASMAR, R. P. **Measurement of thermal conductivity of semiconductors.** *In* Report of the Meeting on Semiconductors, held by the Physical Society, April 1956. p. 119–125.

In measurements made from room temperature to several hundred degrees C, pure iron and stainless steels are used as standard reference materials. Preliminary values are given for the thermal conductivity of Ge, Si, indium antimonide, and indium arsenide.

1148. TAUC, JAN, BEDNAR, J. and ABRAHAM, A. **A method for the precise measurement of thermal emf of samples with great thermal conductivity.** *Czechoslov. J. Phys.* **3**: 314–315, 1953.

In Russian.

Letter. Describes an apparatus in which the two ends of a specimen of the material under investigation (semiconductors are suggested) can be kept at precise and known temperatures. No experimental results.

1149. Westinghouse Research Laboratories, Pittsburgh, Pa. **Rapid measurement of thermoelectric materials under simulated generator conditions,** by S. J. ANGELLO and C. S. DUNCAN. 16 p., figs., Jan. 15, 1959. (Res. Rpt. 431FD406-R1).

Limited availability.

This report is a part of Westinghouse Thermoelectricity Progress Report 12, dated January 1959.

Describes a test apparatus in detail which is fast and sufficiently accurate for evaluating and selecting thermoelectric generator materials.

1150. Air Force, Rome Air Development Center, Griffiss Air Force Base, N.Y. **Design considerations for the radioisotope thermoelectric generator,** by F. B. BRAUER, *et al.* 87 p., Jan. 1957. (Tech. Rpt. 56–130) (AD-97 849) (PB 135 315).

This report consists of five sections, each of which is part of a predevelopment feasibility study of the radioisotope thermoelectric generator. The programme is described in general, and thermoelectric design considerations, radio-isotope source design and shielding are examined in detail. The design of a handling facility is described and a typical electronic application of the device is discussed. The conclusion of this feasibility study are that it is possible to build a practical model of the radioisotope thermoelectric generator and that such a device will have certain unique and desirable performance characteristics not presently attainable by conventional methods.

1151. Air Force. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. **Efficiency of thermoelectric generators,** by J. M. BORREGO, H. A. LYDEN, and J. BLAIR. 75 p., Sept. 1958. (Tech. Note 58–200) (Contract AF33-(616)-3984) (PB 151 748).

The analysis considers efficiency of a thermoelectric generator taking into account the Thomson effect. Results are expressed in terms of macroscopic material parameters such as electrical resistivity, thermal conductivity, and thermoelectric power.

1152. ALFONSO, N. and MILNES, A. G. **Transient response and ripple effects in thermoelectric cooling cells.** 13 p., New York, American Institute of Electrical Engineers, 1959. (AIEE Paper CP 60-174).

The theoretical transient response of a thermoelectric cooling cell is studied under various loading conditions for a step-function of current, and for the effects of sinusoidal ripple currents.

1153. Atomic Energy of Canada, Ltd. Chalk River Project, Chalk River, Ont. **A literature survey on the measurement of thermal conductivity of several solids including uranium dioxide,** by A. M. Ross. 42 p., Mar. 1958. (CRFD-762) (AECL-585).

Various methods for measuring thermal conductivity at ambient and elevated temperatures have been classified into six steady-state heat flow groups and one transient-state heat flow group. The principle of the method of each group is outlined, and a review of pertinent work in the literature is given. An index provides a source of thermal conductivity data for the many materials covered in the survey.

1154. BACKSTROM, M. **The Peltier effect—the future way of operating household refrigerators?** *Kyltek. Tid.* no. **5**: 72–74, 1955.

In Dutch.

"The use of thermocouples has been suggested previously for refrigeration. The known principles of Peltier cooling are summarised, and the efficiency is computed as a function of thermoelectric power, resistivity and heat conductivity. Materials are needed which have a thermoelectric power in excess of 200 microvolts/C and normal Wiedemann–Franz–Lorenz relations. The computations are applied to alloys used by Forsberg. The largest calculated temperature drop is 27·4°C. The efficiency is not as high as that of commercial absorption-type refrigeration. Further development is clearly indicated." *Appl. Mech. Rev.* **9**: 1233, Apr. 1956.

1155. BASSETT, C. D. **Minimizing heat losses in a thermoelectric generator.** *Power Eng.* **54**: 66–67, 106, Oct. 1950.

A discussion of the Denzig method for improving the efficiency of thermoelectric generators and a presentation of a technique for its possible development.

1156. BOLLMEIER, E. W. **An elementary design discussion of thermoelectric generation.** *Elec. Eng.* **78**: 995–1002, figs., Oct. 1959.

This article seeks to acquaint the reader with the elementary problems of thermoelectric generation and some of the solutions that have been devised. Consideration is also given to advantages and disadvantages of thermoelectric generation for uses which may appear desirable at the present state of the art.

1157. BURNS, G. P. **Efficiency of the thermoelectric process.** *Phys. Rev.* **78**: 327, 1950.

"Formulas for the efficiency of the thermoelectric process have been derived for the following cases: (1) External load is different from the internal resistance of the couple. (2) Couple delivers maximum power. (3) Efficiency of the couple is maximum. The maximum efficiency of the process is given by efficiency =

$$\frac{e^2(T_h - T_c)}{e^2T_h + 8pk + 4(pk)^{1/2}(e^2T_h + 4pk)^{1/2}}$$

where e is the thermoelectric power of the couple, T_c the temperature of the hot junction, T_h the temperature of the cold junction, p the specific electrical resistance and k the specific heat conductivity of the elements. If both elements of the couple are made to satisfy the Wiedemann-Franz-Lorenz relation and the temperatures of the junctions are 27°C and 427°C respectively, then for maximum efficiency the external load is 3·91 times the internal resistance of the couple. For e = 1000 microvolts per degree C, this yields an efficiency of 33·9 percent." Entire item quoted.

1158. BURNS, G. P. **Efficiency of the thermoelectric process.** *Phys. Rev.* **78**: 327, 1950.

Abstract only of paper given at meeting of the American Physical Society, February 2-4, 1950, at New York.

Formulas for the efficiency of the thermoelectric process have been derived for the following cases:

(1) External load is different from the internal resistance of the couple; (2) Couple delivers maximum power; (3) Efficiency of the couple is maximum.

1159. DAHLBERG, REINHARD. **Zur Theorie der reversiblen elektrischen heizung. (On the theory of reversible electrical heating).** *Z. Angew. Phys.* **10**: 467–470, Oct. 1958.

In German.

Careful analysis of the heating effects obtainable from thermocouples.

1160. DAHLBERG, R. **Zur theorie der thermoelektrischen kuehlung. (On the theory of thermoelectric cooling).** *Z. Angew. Phys.* **10**: 361–368, Aug. 1958.

In German.

The origins of the thermoelectric effects are examined and the theory of operation of a thermojunction and the design of multijunction coolers are discussed. The results are related to experiments with various materials, in particular, Bi_2Te_3, ZnSb, CdSb, As_2Te_3, and other tellurides and selenides.

1161. Engineering Research Associates, Inc., St. Paul, Minn. **Thermoelectric generators.** 48 p., Nov. 1, 1953. (Rept. PX-71344) (AD-112732).

Presents principle design considerations for a thermoelectric generator based on experimental results achieved in a task aimed at producing a generator to be employed as a charging unit for 6-volt storage batteries.

1162. FRITTS, R. W. **Design parameters for optimizing the efficiency of thermoelectric generators utilizing p-type and n-type lead telluride.** *Comm. & Electron.* **46**: 817–820, figs., Jan. 1960. See also Item 1703.

The thermoelectric properties of p-type and n-type lead telluride systems have been presented to indicate how the figures of merit of these materials vary with temperature. This variation is pronounced and must be taken into account in designing efficient thermoelectric generators for use over different temperature ranges. For thermocouples comprising elements of p-type and n-type lead telluride alloys efficiencies approaching 10% can be anticipated for temperature ranges in which these materials are known to be stable.

The design of optimised thermoelectric generator systems requires fabricating thermoelectric materials such that at each point in a thermocouple element the crystal is doped to provide the maximum figure of merit for the temperature at that point. While the data presented herein pertain to lead telluride systems, the same analysis can be applied to other thermoelectric materials as well.

1163. FRITTS, R. W. **Design parameters for optimizing the efficiency of thermoelectric generators utilizing p-type and n-type lead telluride.** 6 p., New York, American Institute of Electrical Engineers, Jly. 10, 1959. (Trans. Paper 59–909).

The design of optimised thermoelectric generator systems requires fabricating thermoelectric materials such that at each point in a thermoelectric element the crystal is doped to provide the maximum Figure of Merit for the temperature at that point. While the data presented pertains to lead telluride systems, the same analysis can be applied to other thermoelectric materials as well.

1164. GEHLHOFF, P. O., JUSTI, E. and KOHLER, M. **Theories of thermoelectric refrigeration.** *Braunschweig, Wiss. Ges. Abh.* **2**: 149–164, 1950.

In German.

The use of the Peltier effect for refrigeration is discussed. The assumptions and results of the theory of Altenkirch (1912) in which, under idealised conditions, the practical use of the Peltier effect is considered, are briefly stated and discussed. Altenkirch's theory, which is concerned with thermocouple components of cylindrical form only, is then extended to other non-cylindrical forms. It is shown that even a small contact resistance at the cold junction has a considerable harmful effect on the attainable cooling and on the efficiency of the electrothermic process. It is concluded that with modern materials electrothermic refrigeration should now be practically possible.

Digest also appears in *Refrig. Eng.* **58**: 1079, Nov. 1950.

1165. General Electric Co., Schenectady, N. Y. **Some considerations on the effect of constant Thomson coefficients upon the theoretical efficiency of thermopile generators.** by D. L. KERR. 37 p., illus., Sept. 1958. (WADC Tech. Note 58–245) (Contract AF33-(616)5281) (AD-210 835).

Consideration is given to determination of the theoretical efficiency of a thermopile generator when the thermoelectric powers of the materials vary in such a manner that the Thomson coefficients are constant. For such a case, the theoretical expression for efficiency is derived for the condition where the properties of the p and n-type materials are not equal to one another but where the thermal conductivity and electrical resistivity of each material are constant. This expression is then simplified to the case where the properties of the p and n-type materials are equal in magnitude. Calculations were carried out to compare the resulting values of efficiency with the approximate values obtained by using an average figure of merit in the conventional expression for efficiency. This latter expression is that which is obtained by assuming no Thomson effect. These results show that over the range of variables considered, the use of a proper average figure of merit in the conventional efficiency expression will give results of acceptable engineering accuracy. For such cases, use of the more exact and more complicated expression for efficiency is thus not necessary. (TAB p. 5257, Dec. 1, 1959).

1166. General Electric Co., Schenectady, N.Y. **Some considerations of required radiating surface area for thermopile generators in space applications,**

by D. L. KERR. 28 p., Aug. 1958. (WADC Tech. Note 58–244) (Contract AF33(616)-5182).

Consideration is given to the radiating surface area required to reject, by means of thermal radiation, the waste heat from a power package located in space. Particular emphasis is placed upon the case where such a space power package is a thermopile generator. Some of the information, however, is applicable to the general case of any space power package which rejects heat by means of thermal radiation. For a thermopile generator in a space application rejecting waste heat by means of thermal radiation, it is shown that there is an optimum cold junction temperature for minimum required area of radiating surface assuming a given figure of merit and hot junction temperature. It is further shown that when the cold junction temperature is assumed to be equal to the temperature of the radiating surface, the ratio of this optimum cold junction temperature (absolute) to the temperature (absolute) of the hot junction shows little variation with either hot junction temperature, figure of merit, or the ratio of external electrical resistance to the resistance of the thermoelectric materials. For operating conditions in the ratio of interest, this ratio lies between 0·75 and about 0·80 except for very low hot junction temperatures in cases where solar radiation is absorbed. Values of the minimum required radiating surface area and overall thermal efficiency under such conditions are given for a wide range of materials, properties and hot junction temperatures.

1167. GOLDSMID, H. J. **Use of semiconductors in thermoelectric generators.** *Res.* **8**: 172–176, 1955.

Discusses efficiencies, figure of merit, selection of semiconductors, and practical cnosiderations.

1168. GOLDSMID, H. J. and DOUGLAS, R. W. **The use of semiconductors in thermoelectric refrigeration.** *Brit. J. Appl. Phys.* **5**: 386–390, Nov. 1954.

Factors governing the selection of suitable semiconductors are discussed. The material should have a high atomic weight and the thermoelectric power should lie between 200 and 300 μV per degree C. Calculations show that the maximum cooling obtainable with an n-type Ge/metal junction is about 2 degrees C, but that cooling of as much as 28 degrees C should be obtainable with a p-type-Bi_2Te_3/Bi junction; cooling of 26 degrees C was actually obtained using elements of length 1 cm and respective cross-sections of 0·25 cm^2 and 0·03 cm^2, with a current of 6·5A. The calculated figure of merit was 0·475. The possible application of the inverse effect in solar-energy thermoelectric generators is mentioned.

1169. Great Britain. Telecommunications Research Establishment, Farnborough, Hants. **Notes on design of radiation thermocouples.** 4 p., June 29, 1948. (Memo. L3/49/-TSM).

Using materials of given thermoelectric powers, the expected performance of a thermocouple made of these materials is calculated, and the figures compared with characteristics of some thermocouples made at TRE.

1170. GREEFF, M. B. **A note on thermoelectric generation of current.** *J. Appl. Phys.* **21**: 943, 1950.

Telkes has given a formula for the efficiency of any thermocouple for which the Wiedemann-Franz–Lorenz law applies. Calculations show that the efficiency of a thermocouple may be much higher than has been hitherto anticipated provided that couple delivers power above 200μV per °C.

1171. HARMAN, T. C. **Multiple stage thermoelectric generation of power.** *J. Appl. Phys.* **29**: 1471–1473, Oct. 1958.

The efficiency equation for any number of thermoelectric generators thermally in series is derived. The design relationships for maximum efficiency and for maximum power transfer of a multiple stage thermoelectric generator are also given. Since the efficiencies are approximately additive, an appreciable increase in generator efficiency is anticipated by use of multiple stages.

1172. IOFFE, A. F. and others. **Thermoelectric cooling in refrigeration engineering.** *Kholod. Tekh.* **33**: 5–16, 1956.

In Russian.

Translation in Infosearch Tech. Lit. Info. Serv. Semiconductor Applications. Russian Lit. Survey SEM-3-57, p. 1·1–1·22, illus., June, 1957.

The article is devoted to a brief outline of the physical phenomena which form the basis of thermoelectric cooling, discussion of the principal thesis of the theory of thermoelectric cooling evolved by Acad. A. F. Ioffe, and description of the first thermoelectric refrigerators constructed in Russia.

1173. IOFFE, A. F. **Thermoelectric generators.** *Akad. Nauk. SSSR. Ser. Fiz. Dok.* **20**: 76–80, Jan. 1956.

In Russian.

Translation in Infosearch Tech. Lit. Info. Serv Russian Lit. Survey SEM-1-56, p. 1·1–1·6.

Basic design formulas are given and discussed. Using a semiconductor layer 0·5 cm thick, with thermoelectric coefficient 170 × 10^{-6} V/deg., a temperature difference of 300°C across it, and a heat input of 11·6 W/cm_2, and assuming a specific mass of 5 and an efficiency of 8 per cent, an output of 0·2 kW/kg may be obtained.

1174. IORDANISHVILI, E. K. **On the efficiency of refrigeration thermoelements.** *Fiz. Tverdovo Tela.* **1**: 654–665, Apr. 1959.

In Russian.

Trans. in *Soviet Phys. Solid State.* **1**: 595–596, Apr. 1959.

It is shown that by taking the non-linear temperature distribution into account along the branches of a refrigeration thermoelement, and at the same time taking into account the temperature variations of the thermal emf, the electrical conductivity and the thermal conductivity of the

material from which the thermoelement is made, it is possible to express the efficiency of the thermoelement as $Z = \alpha^2\sigma/k$, a function of the temperature differential across the thermoelement. It is established experimentally that for modern thermoelements ($\triangle$Tmax = °60), z increases by 20 to 25% for $\triangle$Twork = 5 to 10°.

1175. JENSEN, H. H. and MEYER, N. **Thermoelectric effects in semiconductors and their practical application in refrigerating elements.** *Ing.* **68**: 165–175, Mar. 1, 1959.

In Danish.

The various thermoelectric effects are defined and a qualitative explanation given of their physical origins and of the reason why their magnitude in semiconductors greatly exceeds that in metals. The Peltier effect is calculated for an extrinsic semiconductor using classical statistical treatment. The maximum attainable temperature difference and the efficiency of the element are calculated as functions of z, making certain simplifying assumptions. Experimental and theoretical bases for choice of optimum semiconductor composition are considered. Recent work has enabled a temperature difference of 80°C (from − 80° to 0°C) to be obtained using bismuth telluride as a semiconductor. The use of the Peltier effect in the design of small domestic refrigerators is discussed.

1176. KERR, D. L. **Radiator areas of thermopile generators in space.** *Aero/Space Eng.* **18**: 57–62, 66, figs., Sept. 1959.

It is shown that there is an optimum cold junction temperature resulting in a minimum required area of radiating surface for given material properties and a given hot junction temperature. The ratio of this optimum absolute cold junction temperature to the absolute hot junction temperature lies between 0·75 and 0·80 for a wide variety of conditions. Resulting values of the minimum required radiating surface area and overall thermal efficiency are presented for a broad range of material properties and hot junction temperatures.

1177. KUCH, A. **Efficiency of thermoelectric generators.** *Elektrotech. Z.* **78**: 182–187, Mar. 1, 1957.

In German.

Mathematical. Equations deduced for calculation of the efficiency of the generation of electricity from heat through thermocouples. The efficiency at first increases quadratically with the thermo-emf, then approaches a peak asymptotically. At TE coefficients of 2 to 5 mv/°K. the generator reaches 80 to 90% of the Carnot efficiency. To get load balancing from high output generators, the external resistance must be made very much larger than the internal resistance as in normal d.c. generators. The optimum load resistance is independent in this case of the operating temperature and TE properties of the generator within wide limits. The case of couples of low TE effects is also discussed.

1178. LUKACS, JOZSEF. **Thermoelectric generators using semiconductors.** *Elektrotekhnika.* **50**: 121–130, Apr. 1957.

In Russian. Not examined.

Certain industrial applications are discussed of thermoelectric generators and their efficiency studied. The potentialities are investigated of building a thermoelectric generator with semiconductors based on the Nernst-Ettingshausen effect. Certain theoretical aspects are treated.

1179. MACHLUP, S. **Efficiency of a thermoelectric engine.** *Am. Phys. Soc. Bull.* **3**: 129, Mar. 27, 1958.

Abstract only.

Concerns suggestions for finding the most efficient operating conditions.

1180. MADELUNG, OTFRIED. **Theory of conduction in isotropic semiconductors.** *Z. Naturforsch.* **9a**: 667–674, Jly./Aug. 1954.

In German.

The classical theory is developed and the equations for electrical and thermal current density are established. From these equations the coefficients of all the galvanomagnetic, thermoelectric and thermomagnetic effects are derived. Expressions for these coefficients are tabulated for small values of magnetic field strength, for degenerate and non-degenerate semiconductors with given scattering mechanism.

1181. Martin Co. Flight Vehicles Design Department, Baltimore, Md. **Silent electric generator utilizing thermoelectrics,** by A. A. SORENSEN. 17 p., illus., Oct. 1958 (ADA R-013) (Res. Memo. 11).

The concept of an electric generator utilising thermoelectric elements is outlined and the advantages for military use due to its quiet operation described. Calculations are used to determine the parameters required of the elements in order to produce an output of 1000 watts. Values from heat transfer calculations and the resulting size and weights are tabulated.

1182. Massachusetts Institute of Technology, Cambridge, Mass. **Thermoelectric effects in silver halides,** by WALTER GRATTIDGE. 15 p., 1954. (Tech. Rept. 272).

The theory of electric conductivity and thermoelectric effects in ionic crystals is reviewed briefly. AgCl and AgBr crystals in well-annealed, quenched, and intermediate states were measured. Ag electrodes were deposited chemically on opposite surfaces of each specimen. Ni electrodes were attached, and the entire assembly mounted in an evacuated glass envelope. Data are reported over the temperature range 30–300°. For AgBr, conductivity and thermal emf are independent of the previous history of the sample. This is not true of AgCl. Previously reported data are compared. An appendix contains a description of a scale

expander used to modify a 10- or 25-mv recording potentiometer for various full-scale ranges from 0·5 to 10 mv.

1183. Massachusetts Institute of Technology. Servomechanisms Laboratory, Cambridge, Mass. **The efficiency of thermoelectric generators,** by J. M. Borrego, H. A. Lyden and John Blair. 75 p., illus., Sept. 1958. (WADC Tech. Note 58-200) (Contract AF33(616)-3984) (AD-206-383).

The thermoelectric effects are described and the efficiency of a thermoelectric generator is developed based upon the assumptions that the thermal conductivity, the electrical resistivity and the Thomson coefficient are constant along the length of the material. This development differs from the usual ones presented in the literature in that the thermoelectric power is not assumed to be constant but instead is assumed to vary with temperature in a manner so that $\gamma = Td\alpha/dT$ is a constant. The resulting expressions for the efficiency and the figure-of-merit differ slightly from those previously reported in the literature. This difference is investigated in detail with respect to the expressions developed by A. F. Ioffe. An analysis is presented concerning the dependence of the efficiency of a thermoelement upon its doping concentration and a procedure is developed for maximising the efficiency as a function of this parameter. Lastly the case of temperature dependent k, p and is investigated and equation are developed by which, if the temperature dependence of these parameters is known one can accurately determine the material's efficiency as a thermoelectric generator.

1184. Momota, Tsuneo and Matsukura, Yasuo. **Efficiency of solar thermoelectric generators composed of semiconductors.** *Conf. Uses of Solar Energy, Tucson,* 1955, Trans. **5**: 21–30, 1955.

Some general theoretical equations were derived for the efficiency of semiconductor thermogenerators at maximum output, both for the degenerate case and the non-degenerate case. The values are plotted as a function of k/μ, where K is heat cond. (watt cm.$^{-1}$ C^{-1}) and μ is carried d. (sq. cm. v.$^{-1}$ sec.$^{-1}$) for various values of n, the carrier d (cm^{-3}), at $T_1 = 500$ K and $T_0 = 300$ K. For any kind of semiconductor, the efficiency does not exceed 20% for these temperatures. Experiments on TiO_2 semiconductors are described. The observed values are somewhat higher than the theoretical values, and this discrepancy is discussed. For the above temperatures, the maximum efficiency observed was about 1. It is suggested, for the general semiconductor generator, that materials having low values of k/μ and having high carrier d., n, be used. The efficiency of PbTe (for $k/\mu = 2{\cdot}5 \times 10^{-5}$ and $n = 10^{20}$) is 16% for the above temperatures.

1185. North Carolina State College, Raleigh, N.C. **The measurement of thermal properties of nonmetallic materials at elevated temperatures,** Final Report, by K. O. Beatty, Jr. and A. A. Armstrong. 59 p., June 30, 1956. (ORO-170) (Contract AT (40-1)-1319).

In the first part the principal results of the mathematical analysis are given in useful form and a description of the application of these results to the interpretation of data from experimental runs is given. In the second part a more detailed account is given of the 13 different sets of boundary value problems and their solutions that have been used in narrowing the gap between mathematically judicious and physically possible conditions.

1186. O'Brien, B. J. **Cascading of Peltier couples for thermoelectric cooling.** *J. Appl. Phys.* **27**: 820–823, Jly. 1956.

The cooling of a single thermoelectric junction is limited to a certain temperature difference by the properties of the elements used, but this limitation may be overcome by using a number of thermocouples in thermal cascade. A simplified theory of this is given, and results in good agreement are obtained with a two-stage cascade which is described in detail. It is shown that such a cascade is in theory more efficient than a single couple in all circumstances.

1187. Papet, R. **Remarks on the efficiency of thermoelectric generators.** *J. Appl. Phys.* **19**: 1180, 1948.

Discussion of Telkes' formulae for calculating the efficiency of thermoelectric generators.

1188. Perking, J. F. **Optimum loading of a thermoelectric generator.** *J. Appl. Phys.* **25**: 1058, Aug. 1954.

It is shown that the maximum efficiency corresponds to maximum output. For typical cases, efficiencies as high as 30-40% should be possible.

1189. Perkins, J. F. **Optimal loading of a thermoelectric generator.** *J. Appl. Phys.* **25**: 1058, Aug. 1954.

Discussion of Telkes' method for calculating TE generator efficiency.

1190. Peschke, K. **Thermoelements and thermoelectric d.c. generators.** *Arch. Elektrotech.* **43**: 328–354, Nov. 29, 1957.

In German.

"Detailed theoretical investigation of thermodynamic efficiency taking account of the various thermoelectric effects, and changes in resistivity and thermal conductivity. Higher efficiencies should be obtainable than those indicated by other authors. Problems of construction and mechanical strength are also considered." *Electron. & Radio Engr.* **35**: A170, Oct. 1958.

Abstract also in *Sci. Abs.* **61B**: 1340, Mar. 1958.

1191. Ritchey, B. B. and Vogelsang, C. A. **Current from temperature.** *Instrumentation* **9**: 25–28, Sept./Oct. 1956.

Discusses several basic laws governing thermocouples from the standpoint of their practical application.

1192. SCHUH, N. F. and TALLENT, R. J. **Solar-powered thermoelectric generators design considerations.** *Appl. & Indus.* **45**: 345–352, illus., Nov. 1959.

This paper presents, in a brief manner, some of the principles and problems which may be expected in applying solar energy to a thermoelectric generator serving a space vehicle and also describes a small solar-powered thermoelectric generator which was constructed to study these problems. Article with same title appears in *Elec. Eng.* **78**: 1172–1176, Dec. 1959. Also issued as AIEE. Transactions Paper 59–847.

1193. SHERMAN, B., HEIKES, R. R. and URE, R. W., JR. **Calculation of efficiency of thermoelectric devices.** *J. Appl. Phys.* **31**:1–16, figs., Jan. 1960.

A procedure has been developed for the exact calculation of the efficiency of thermoelectric generators and cooling devices in which the parameters of the materials have arbitrary temperature dependence. High-speed computer techniques are found necessary. Approximate methods are reviewed and their discussion extended. A number of examples are worked out by both the exact and approximate methods. Comparison of these results show that the approximate methods agree with the exact method to about 5% in the case of power generation and to about 15% in the case of the refrigeration coefficient of performance. However, in the case of the maximum heat pumping rate deviations as large as a factor of 2 are found.

1194. STIL'BANS, L. S. and FEDOROVICH, N. A. **On the work of cooling thermoelectric cells under non-stationary conditions.** *Zhurn. Tekh. Fiz.* **28**: 489–492, Mar. 1958.

In Russian.

Translation in Infosearch Tech. Lit. Info. Serv. Russian Lit. Survey SEM-5-58, p. 11·1–11·5.

The operation of a cooling thermoelement under transient conditions has been studied theoretically and experimentally. It is shown that the inertial (lag) of the thermoelement is proportional to the square of its linear dimensions. The lad depends also on the working current and may be reduced to a fraction of its normal value by using pulsed current with an amplitude exceeding the value of the optimum current with stationary conditions. Under pulsed operating conditions, a thermoelement may for a short period of time attain temperatures much lower than the minimum temperature attainable under stationary conditions.

See also *Soviet Phys. Tech. Phys.* **3**: 460–463, Mar. 1958.

1195. STIL'BANS, L. S. **O viborie sootnoshcheniya sechenii vetviu poluprovodikovikh termoelementov. (On selection of correlation of branches in a semiconductor thermoelectric cell).** *Zhurn. Tekh. Fiz.* **28**: 262–263, Feb. 1958.

In Russian.

Translation appears in Infosearch Tech. Lit. Info. Serv. Russian Lit. Survey SEM-5-58, p. 9·1–9·2.

Ioffe has shown that the efficiency of a thermoelectric cooling element is maximised when the ratio of the cross-sectional areas of the two components has a calculable value. The author shows that in such a case there is only a very small reduction in efficiency if the ratio is made unity for simplicity of manufacture.

1196. STRATTON, R. **The figure of merit of a thermoelectric generator.** *J. Electron & Contr.* **7**: 73–76, Jly. 1959.

Optimum conditions are deduced for a thermoelectric generator or refrigerator with n- and p-type semiconducting branches which have different physical parameters. The results are related in a simple manner to the previously calculated optimum conditions for the individual figure of merit of a single substance.

1197. SWANSON, B. W. and SOMERS, E. V. **Optimization of a conventional-fuel fired thermoelectric generator.** *J. Heat Transfer.* **81**: 245–248, figs., Aug. 1959.

The purpose of this report has been to investigate conditions for optimising the thermal efficiency of the design of a conventional-fuel-fired thermoelectric generator. Equations have been developed for the following: (1) The temperature distribution of the heated gas in a circular duct type of generator, that maximises the thermoelectric power output, with respect to the temperature distribution within the duct and the exit gas temperature at the end of the duct; (2) The thermoelectric power developed, based upon these optimising temperature criteria; (3) The required variation of thermoelectric element thickness required to satisfy both optimising temperature criteria; (4) Thermal efficiency under optimum conditions.

1198. TELKES, MARIA. **Power output of thermoelectric generators.** *J. Appl. Phys.* **25**: 1058–2059, Aug. 1954.

Discussion of TE generator efficiency calculation.

1199. UCHIYAMA, S. **Theory of thermoelectric refrigeration.** *Nagoya Univ. Mem. Fac. Eng.* **9**: 321–329, Nov. 1957.

"A theory of the temperature distribution in the n-type and p-type elements of a thermoelectric refrigerator, that takes the Thomson effect into account and eliminates earlier discrepancies between experimental results and theoretical values is developed. Whereas the maximum temperature difference is smaller, the current corresponding to the maximum temperature difference is larger than predicted by earlier theories. The effect of changing the carrier concentration, along the direction of current flow, and the cross-sectional area of the elements to achieve a maximum temperature difference is investigated." *Sci. Abs.* **62A**: 2366, 1959.

1200. VIKHOREV, G. and NAER, V. **The effect of heat-transfer on the characteristics of semiconductors and heat-pumps.** *Fiz. Tverdogo Tela.* **1**: 903–907, June 1959.

In Russian.

"A linear heat-transfer coefficient is assumed between each reservoir and the corresponding thermocouple junctions. The regime of the thermopile at given reservoir temperatures is calculated as a function of working current. The dependence of optimum current on the heat-function coefficient is examined for a range of practical values, and found to be negligible, although the efficiency, and other parameters, are considerably altered. [The quantity z not defined in the text, should read as $(e^2/p\lambda)$ deg^{-1}]." (*Sci. Abs.* **62B**: 7217, Dec. 1959).

1201. Westinghouse Electric Corp., Pittsburgh, Pa. **Weight and volume considerations in design of thermoelectric generators.** by E. V. SOMERS, 6 p., fig., Nov. 6, 1957.

(Res. Memo. 8-0867-M2X). Limited availability.

1202. Westinghouse Research Laboratories, Pittsburgh, Pa. **Optimization of the available power of a closed-cycle thermoelectric generator,** by B. W. SWANSON and E. V. SOMERS. 11 p., figs., Oct. 23, 1958. (Res. Rpt. 431FD282-R5-X).

Limited availability.

This report is a part of Westinghouse Research Thermoelectricity Progress Report 12, dated January 1959.

1203. Westinghouse Research Laboratories. Pittsburgh, Pa. **Thermoelectricity.** 35 p., Oct. 10, 1958, (Prog. Rpt. 9) (Contract NObs-72361).

Limited availability.

RR431FD282-R4-X, Optimization of the Available Power and Power Density of a Fuel-Fired Thermoelectric Generator, by B. W. Swanson and E. V. Somers, 17 p. RR414FD307-R1, Design Procedure for Thermoelectric Power Generators, by S. J. Angello, 18 p.

APPLICATIONS

(Power Generators)

1204. ACHESON, E. G. **Thermoelectric generator.** U.S. Patent 375, 242, Dec. 20, 1887.

A passage of heat through gas films produces an emf in this generator. A mixture of bioxide of manganese and chlorate of potash is contained in a cylindrical jacket which surrounds a gas burned. Oxygen enters the mixture at the bottom and escapes from it at the top of the cylinder. The emf is generated between the top and bottom of the cylinder.

1205. Armour Research Foundation, Chicago, Ill. **The design, development and construction of a heat production and distribution device,** by H. E. ROBINSON. Final Report. Sept. 30, 1953. (Contract DA44-109-qm-1154).

Part I. Thermoelectric generators, p. 100–108.

Appendix A—Thermoelectric principles and data, p. A1-A20.

1206. ARVIN, M. J. **Thermoelectric generator and methods for production of same.** U.S. Patent 2,702,828 (to Milwaukee Gas Speciality Co.).

A thermoelectric generator comprising an annular electrically insulating disc having a generally axial opening therein, a first thermoelectric generator material in the form of a circumferentially continuous coating disposed solely on one side of said disc and partially around the inner edge of said disc at the periphery of said opening, and a second dissimilar thermoelectric generator material disposed solely on the other side of said disc, and partially around the inner dege of said disc at the periphery of said opening and meeting and electrically joined endwise along the inner edge of the disc at the periphery of the opening therein to the contiguous edge of the said first thermoelectric generator material to form a thermojunction which is circumferentially continuous about the periphery of said opening.

1207. **"Atomic battery": direct conversion from atomic radiation to electrical energy.** *Direct Current.* **2**: 135–137, Sept. 1955.

Mound Laboratory, operated by Monsanto Chemical Company for Atomic Energy Commission, has developed "atomic battery" which makes use of series of thermocouples joined to make up a thermopile for purpose of converting heat from radioactive decay into electrical energy; present state and possible future of this development.

1208. BARMAT, M., ANDERSON, G. M. and BOLLMEIER, E. W. **Snap-III-electricity from radionuclides and thermoelectric conversion.** *Nucleonics.* **17**: 166–174, May 1959.

A demonstration model of a radio-nuclide battery is described. It is designed to generate electrical power from the heat of radioactive disintegration. The model consisted of a small central heat source containing 1,760 curies of Po^{210}, 54 semiconductor thermoelectric elements, and an outer shell designed to radiate heat to full space. The characteristics of a full-scale device are tabulated.

1209. BASSETT, C. D. **Practical thermoelectric generator.** *Power Generation,* **53**: 74-77, Aug. 1949, discussion, **54**: 76–78, Jan. 1950.

The Peltier effect, the thermodynamics of electrical phenomena, the Fitterer thermocouple and its construction and use in the steel industry are discussed. Proposes a thermoelectric generator, and discussed theory and practical construction.

1210. **Bathroom heater employing thermoelectric principle developed by Lone Star Gas Co.** *Gas Age,* **124**: 30–31, illus., Oct. 15, 1959.

Designed for ceiling installation, the unit combines the use of a recently developed radiant type burner for its heat source and a series of 24 small thermocouples to generate thermoelectric energy. The latter power a built-in handling fan to increase efficiency of the unit by recovering a portion of the exhaust heat. The automatic valve controls are also operated by thermoelectricity. The heater operates on gas. Design characteristics, illustrations, and costs are given.

1211. BAUM, V. A. and OKHOTIN, A. S. **Test results of two experimental solar thermoelectric generators.** *Teploenergetika.* p. 68–70, 1957.

In Russian.

Tests on the STG-1 and STG-2 generators are recorded. Both contained 70 blocks, each of 12 ZnSb–constantan thermocouples. The STG-2 generator was used with a paraboloid mirror and produced 18·9 W at 21 V. The efficiency of the generator was 1·42% and that of the whole plant 0·8%.

1212. BETZ, G. **E. Raub's new thermoelectric battery.** *Elec. Rev.* **22**: 332, 1888.

Three different models of the Raub generator are described. Their output ranges from 25 watts for the smallest to about 68 watts for the largest. Each model has an emf of 3 volts. Each generator comprises a vertical cylinder with a gas burner at the bottom.

1213. BETZ, W. L. **A.C. Release of thermoelectric devices.** *Elec. Eng.* **74**: 227–230, Mar. 1955.

Thermoelectric shut-off devices are used to discontinue operation of gas burners should pilot flame be extinguished or decreased to unsafe proportions: these devices can be made to operate in response to situations other than the pilot flame conditions by superposition of a.c. on thermoelectric current flowing through electromagnet winding; a.c. release may be employed for limit control operations or as usual means to terminate burner operation. (AIEE conference paper CP55-237).

1214. BRIGGS, J. L. and SIROIS, L. J. **Radioisotope thermoelectric generator.** *Inst. Radio*

Engrs. Convention Record 5 (Pt. 9): 69–74, 1957.

Recent advances in the field of solid-state physics have greatly enhanced the possibility of developing a practical thermoelectric generator for power supply electronic equipments. The possibility of utilising an efficient thermopile driven by decay energy derived from isotopes is suggested. The course of development of this device at RADC will encompass three problem areas: (1) geometry and packaging of radioisotope thermal source; (2) development of efficient thermopile, and (3) consideration of circuits best suited to this type of power supply.

1215. CLARK, L. **Clamond's thermoelectric battery.** *Elec. Rev.* **4**: 154–157, 1876.

Several different models of the Clamond generator are described. They vary in output from 1·5 to 25 watts. Twenty elements give about one volt. Operation of the generators requires about one cubic foot of gas per hour per twenty elements. The positive element is comprised of two parts Sb and one part Zn, and the negative of tinned sheet iron.

1215. COOK, J. J. **Thermoelectric generator.** U.S. Patent 1,083,191, Dec. 30, 1913.

A compact thermoelectric generator has plate-elements of: (1) an antimony-selenium alloy, and (2) a bismuth aluminium alloy. Steam is fed into a central duct located within the vertically stacked hot junctions. Cold water is fed into a similar duct located within the stack of cold junctions. After considerable use the steam and the cold water feeds may be reversed. The current flow will then be reversed and deterioration caused by prolonged use with current flowing in one direction will be nullified.

1216. COVE, G. H. **Thermoelectric battery and apparatus.** U.S. Patent 824, 684, June 26, 1906.

A generator comprises vertical elements of antimony imbedded in a block of non-combustible insulating material. The positive elements are alternately German silver and copper. The output is about 1·5 watts.

1217. COX, H. B. **Cox thermoelectric generator for the conversion of heat directly into electrical energy.** *Elec. Eng.* **19**: 383–385, 1895.

Three different models of the Cox Generator are described. They vary in output from 27·5 to 275 watts. The large generator resembles a coal-burning stove. An external water jacket cools the cold junctions.

1218. COX, H. B. **Thermoelectric battery.** U.S. Patent 434, 427, Aug. 19, 1890.

The novelty of this invention lies in the method of cooling the cold junctions. Curlicue radiator strips protrude from the cold ends of the elements.

1219. COX, H. B. **Thermoelectric generator.** U.S. Patent 434, 428, Aug. 19, 1890.

A generator is in the form of a cylindrical furnace. A water jacket on the outside cools the outer junctions.

1220. COX, H. B. **Thermoelectric generator.** U.S. Patent, 434, 500, Aug. 19, 1890.

The hot junctions of this generator are coated with fireproof cement which holds them together around the central heat source.

1221. COX, H. B. **Thermoelectric generator.** U.S. Patent 529, 711, Nov. 27, 1894.

Hot water circulates around the hot junctions of the generator. A separate water cooling system maintains the cool junctions at a lower temperature.

1222. COX, H. B. **Thermoelectric generator.** U.S. Patent 525, 488, Mar. 12, 1895, and also Patents 535, 489 and 535, 490.

Details of construction and improvements are described for a cement-coated thermocouple.

1223. COX, H. B. **Thermoelectric generator.** U.S. Patent 546, 517, Sept. 17, 1895.

Heat is applied to the centre of the thermopile by the circulation of hot air; cooling of the outer junctions is accomplished by circulation of a cooling liquid.

1224. DANIEL'-BEK, V., VORONIN, A. and ROGINSKAYA, N. **Thermoelectric generator TGK-3.** *Radio* (*USSR*). p. 24–26, Feb. 1954.

In Russian.

Description of a paraffin-lamp-driven generator for use with battery-type receivers. The outputs are 2V 2A for the vibrator ht unit and 2V 0·5A for heaters. A 1·2-V, 0·36A tapping is also provided. Semiconductor-type thermoelements are mentioned as being more efficient than pure-metal thermocouples.

1225. DARRAH, W. A. **Thermocouple.** U.S. Patent 1,667,142, Apr. 24, 1928.

The thermoelectric converter of electric energy comprises German-silver and antimony elements which are sprayed on asbestos sheets. Its output is 2 or 3 amperes at 6 volts. The heating means is an electrically heated nichrome coil.

1226. DUCH, GABRIEL. **Thermoelectric battery.** U.S. Patent 1,587, 707, June 8, 1926.

The generator comprises a stack of wire crowns, each formed of alternate portions of iron and constantan, and a central duct designed to carry waste heat. The maximum output is claimed to be 58 milliamperes at 62 volts, or 6 watts.

1227. DUNN, R. H. **Means for constructing a thermopile and for utilizing solar rays and other energy for the purpose of generating, transmitting, storing and using thermoelectricity.** British Patent 14,033, Jly. 7, 1899.

An enveloping roof, transparent or opaque as desired, nonconducting both as regards heat and electricity and adapted to hold a thermoelectric arrangement of suitable metals or other substances, called a heliopile, for the purpose of transmitting solar heat or other energy into electricity.

1228. EASTWOOD, W. S., MULLETT, L. B. and PUTMAN, J. L. **American miniature nuclear generator, snap III.** *Nature*, **183**: 643–644, Mar. 7, 1959.

A note on a power supply system for telemetry apparatus in a space rocket. The decay energy of a radioactive Po capsule is converted directly to electrical energy by means of thermocouples, giving an output of 5 w with efficiency 8–10 per cent.

1229. Eureka Williams Corp., Bloomington, Ill. **Progress report no. 1.** 20 May—30 June 1955, by L. G. WALLER, n.p., Jly. 28, 1955. (Contract Nord 15993) (AD-116G95).

500 and 30-volt thermal batteries.

1230. FARBER, E. A. and GLICKSTEIN, M. R. **Effects of junction manufacture on thermocouple emf generation.** Paper 56-A-135 given at ASME Annual Meeting, New York, Nov. 1956. 6 p.

1231. FAUS, H. T. and RIDGLEY, D. E. **Tellurium-bismuth thermoelectric element.** U.S. Patent 2,788,382 (to General Electric), Apr. 9, 1957.

A Te thermoelectric element containing 0·01–0·1% Bi gives an emf of about 300 microvolts/°C against Cu. The variation of emf with temperature is essentially linear from 50 to 150°. Electric resistivity and emf against Cu range from 0·03 ohm/cm and 360 microvolts/°C for an alloy containing 0·01% Bi to 0·01 ohm/cm and 300 microvolts/°C for an alloy containing 0·1% Bi. The thermocouples are operated at a hot junction temperature of 150° and the cold junction at 50°. The resistivity values are measured at 50°.

1232. FINDLEY, H. J. **Thermoelectric generator.** U.S. Patent 2,410,872, 7 p., illus., Nov. 12, 1946.

Manually portable upright thermoelectric generator with housing and base of novel construction and containing a compactly arranged liquid fuel burning means and thermopile.

1233. FINDLEY, H. J. **Thermoelectric generating device.** U.S. Patent 2,415,005, Jan. 28, 1947.

The upright hollow thermopile has internal hot junctions and external cold junctions. An air stream cools the outer junctions.

1234. **First—the frame of reference—Moscow today.** *Prod. Eng.* **29**: 5–8, 10, illus., Jly. 14, 1958.

Includes mention and illustration of a 3-watt thermoelectric generator used in rural areas.

1235. **5000-watt thermoelectric generators.** *Mech. Eng.* **81**: 64, Jly. 1959.

Announces thermoelectric generators to be built by the Carrier Corporation and the Westinghouse Electric Corporation for the U.S. Navy Bureau of Ships.

1236. Franklin Institute, Philadephia, Pa. **Development of thermocouples for use on thermoelectric generators.** 10 p., 1951. (Quart. Prog. Rpt. P-2205-4).

Summarises work from July 1—September 30, 1951, on a programme of theoretical and experimental research conducted for the purpose of improving understanding of the thermoelectric properties of materials and of developing a thermocouple of improved efficiency for use in thermoelectric generators. Concerned principally with the development of processes for quantity production of Zn-Sb thermocouple elements and suitable means for soldering or fusing these elements to constantan. Preparation and thermoelectric properties of PbS were investigated. Attention was given to problems involved in transfer of heat from the source to the hot junctions.

1238. FRITTS, R. W. **Thermoelectric generator.** U.S. Patent no. 2,906,801 (to Minnesota Mining and Manufacturing Co.), Aug. 26, 1957.

A thermoelectric generator comprising a pair of thermoelements, a support for said thermoelements, and means including a resilient metallic thermojunction member electrically joining said thermoelements to provide a thermojunction, said resilient member also being operatively associated with said support and exerting a compressive stress on said thermoelement.

1239. GEILUNG, LEONARD. **Die verwendung von thermoelementen in weltraum. (The application of thermoelements in space).** *Weltraumfahrt.* **2**: 59–60, June, 1951.

In German.

Using elements of 90% bismuth and 10% tin, and 75% tin and 25% cadmium, it is possible to obtain 1 KW power in the earth's orbit for a total weight of 150 kgm and surface area of 400 square meters.

1240. GEILING, LEONARD. **Thermoelectric pile for transforming solar energy.** *Rev. Gen. Elec.* **62**: 575–580, Dec. 1953.

In French.

Discusses the behaviour and efficiency of the thermocouple as a source of electric energy when heated by solar radiation collected and directed on to it by mirrors. About 500 kG of material is required per kW and about 1 km² of mirror area for 5000 kW. Internal resistance is high, energy storage is required, and d.c. to a.c. conversion is necessary.

1241. General Electric Co. Knolls Atomic Power Laboratory, Schenectady, N.Y. **Direct conversion of fission energy by the thermoelectric power of semiconductors,** by J. W. MOYER. 5 p., Oct. 26, 1954. (Rpt. KAPL-M-JWM-1) (Contract W31-109-eng-52).

The direct conversion of fission energy to electrical using the enhanced thermoelectric properties of Ge is shown to be potentially the most efficient process considered to date. A sample calculation shows that efficiencies in excess of 15% may be obtained.

1242. GOTTSCHO, L. **Thermoelectric pile.** U.S. Patent 650,062, May 22, 1900.

The elements of the generator are bismuth and antimony. A star-shaped arrangement of wires join the hot and cold junctions.

1243. HALE, L. E. **Thermoelectric battery for motor vehicles.** U,S. Patent 1,134,452, Apr. 6, 1915.

The device is designed to supplant the storage battery on a motorcycle. The thermocouples are long strips lying lengthwise inside the exhaust pipe of the gasoline engine. The cold junction end of the exhaust pipe is equipped with cooling fins.

1244. HEIKES, R. R. **Design of thermoelectric materials for power generation and refrigeration.** Programme of the Fall Meeting of the Electrochemical Society, Sept. 1958.

Abstract only.

An elementary discussion of a thermoelectric power generator was given in order to determine those physical parameters which enter the materials design problem. The present theoretical understanding of these parameters was then discussed.

1245. HEIL, A. **Thermoelectric battery.** U.S. Patent 808,086, Dec. 26, 1905.

A thermopile has a vertically central heating chamber and radially disposed elements.

1246. HEYWOOD, HAROLD. **Mechanical construction and thermal characteristics of solar-operated thermoelectric generators.** Conf. Use Solar Energy, Tucson, 1955, Trans. **5**: 8–20, 1958.

A description is given of the mechanical construction of thermoelectric generators and the heat flow in such systems. The thermocouples were composed of Zn–Sb alloy and constantan. Flat-plate type and vapour-heated thermoelectric generators are considered.

1247. HORNE, R. A. **Forming electrical contacts to thermoelectric materials.** RCA Tech. Notes. **7**: TN 305, Nov. 1959.

Conventional soldering techniques fail to wet bismuth-tellurium thermoelectric materials thus making difficult the formation of a mechanically strong, low electrical resistance junction between these materials and electrical leads.

The arrangement described, with drawing, avoids these difficulties.

1248. HORNE, R. A. and SMITH, L. B. **Forming integral pressed contacts for thermoelectric units.** RCA Tech. Notes **7**: TN 304, Nov. 1959.

The scheme described (with a drawing) concerns a method of making contacts to the thermoelectric materials which contacts are mechanically strong, readily soldered to copper electrical leads by usual methods, and which have a resistance only a few percent of the resistivity of the thermoelectric material of the unit. The arrangement can be used in thermoelectric devices such as refrigerators, air conditioners and power generators.

1249. Horizons, Inc., Cleveland, Ohio. **Thermoelectric generators**, by LLOYD OWENS. Final Report. 60 p., illus., Jan. 10, 1958. (Rpt. RADC-Tech. Rpt.-58-26) (Contract AF30(602)-1634).

This report covers seven months of experimental engineering investigation leading to the construction of five breadboard thermoelectric generators. The maximum efficiency achieved was 1·47% at a load of 2·6 volts with a 10 watt-15 cubic centimeter heat source. Two generators were constructed using chromel versus constantan as the thermoelectric materials; two were constructed using ZnSb plus additions of Bi, Sn, Ag versus constantan, and one was constructed using ZnSb versus Bi–Te alloys. A method of improving commercial insulating materials was found. The design parameters governing the choice of the number of junctions, apportionment of heat flow, temperature difference and internal resistance in their relationship to efficiency was studied.

1250. **Investigations of direct generation of electricity from heat underway.** *Instr. Soc. Am. J.***5**: 72, Jly. 1958.

Brief note on a process involving use of a power plant known as a thermoelectric generator.

1251. IOGANSON, N. E. **Semiconductor generators of control current.** *Elektricheskie Stantsii.* **28**: 74–75, 1957.

Translation in Infosearch Tech. Lit. Info. Serv. Russian Lit. Survey SEM-3-57: 6·1–6·5, illus., June 1957.

Description of thermoelectric generators and their capabilities.

1252. JONES, R. V. **Design and construction of thermoelectric cells.** *J. Sci. Instr.* **11**: 247–257, 1934.

A typical antimony-cadmium alloy cell has a receiving area 0·05 centimeter square and develops 55 microvolts if a candle is placed one meter distant.

1253. JORDAN, K. C. **Thermo-electric generator** (to U.S. Atomic Energy Commission) U.S. Patent 2,844,639, Jly, 22, 1958. *Nuclear Sci. Abs.* **13**: 994, 1959.

The conversion of heat energy into electrical energy by a small compact device is described. Where the heat energy is supplied by a radioactive material and thermopiles convert the heat to electrical energy. The particular battery construction includes two insulating discs with conductive rods disposed between them to form a circular cage. In the centre of the cage is disposed a cup in which the sealed radioactive source is located. Each thermopile is formed by connecting wires from two adjacent rods to a point on an annular ring fastened to the outside of the cup, the ring having insulation on its surface to prevent electrical contact with the thermopiles. One advantage of this battery construction is that the radioactive source may be inserted after the device is fabricated, reducing the radiation hazard to personnel assembling the battery.

1254. KACH, A. **Zur frage des wirkungsgrades thermoelektrischer generotoren. (On the question of efficiency of thermoelectric generators).** *Elektrotech. Z.* **78**: 182–187, Mar. 1, 1957.

In German.

Translation no. 58–1095 available from SLA Translation Center, Crerar Library, Chicago, Ill.

The T-E generator is the simplest arrangement for converting heat to electrical energy. There are no moving parts, only slight wear, great reliability,

it requires almost no servicing and from this it would be preferably suitable also for the conversion of large quantities of high grade energy.

1255. KLOPATEG, P. E. **Thermoelectric device.** U.S. Patent 1,893,748, Jan. 10, 1933.

The single thermocouple device is designed for use in demonstrating thermoelectric effects. It is claimed that a 300 ampere current is obtained at 10 to 12 millivolts when a temperature gradient of 350°C is maintained. The elements are copper and copper-nickel.

1256. LAUTENSACK, D. **Thermoelectric battery.** U.S. Patent 313,215, Mar. 3, 1885.

A cylindrical centrally heated thermopile has elements of copper-nickel and antimony-zinc.

1257. LEE, J. M. **Thermoelectric generator for portable equipment.** *Electron.* **19**: 196, 202, May, 1946.

Banks of chromel-P/constantan thermocouples embedded in ceramic material and heated by a gasoline burner give power outputs up to 20 watts at 12 volts. The couples have a useful life of about 2000 hours. and the generator weighs about 2½ pounds per watt output.

1258. LINDEN, D. and DANIEL, A. **New power sources for space-age electronics.** *Electron.* **32**: 43–47, Mar. 20, 1959.

Brief discussion of the 5-watt thermoelectric unit designated SNAP-III by the AEC. This device was developed by the Martin Co. and Minnesota Mining & Manufacturing Co. The thermoelectric material used is lead telluride alloyed with other substances, and the radioisotope Po-210. With 3000 curies of radioactivity SNAP-III will generate electricity at the rated capacity of 5 watts with an efficiency of 8–10 per cent.

1259. LINDENBLAD, N. E. **N-type thermoelectric devices.** U.S. Patent no. 2,846,493, 3 p., illus., Aug. 5, 1958.

Improved thermoelectric devices including high melting point gold-nickel thermoelectric alloys.

1260. LINDENBLAD, N. E. **Thermoelectric devices** U.S. Patent no. 2,846,494, 3 p., illus., Aug. 5, 1958.

Improved thermoelectric device including high melting point iron-aluminium thermoelectric alloys.

1261. LUEBKE, E. A. and VANDENBERG, L. B. **Compact reactor power plant with combination heat exchanger—thermoelectric pump.** *Nuclear Sci. & Tech.* **4**: 167–176, Mar/Dec. 1954.

A compact reactor power plant is described in which the reactor proper is located within a cylindrical heat exchanger. The pumping action in this liquid-metal-cooled reactor system is obtained in combination with the heat-exchanger function. By interposing thermoelements a large thermoelectric current is generated in the cylindrical heat exchanger by means of the temperature gradient normally existing between hot and cold tubes. With suitable pole pieces this current produces a perpendicular magnetic field and develops sufficient force on the liquid metal for the desired pumping action.

1262. MARCUS, S. **A new and very powerful thermoelectric battery.** *Am. J. Sci.* **40**: 257–258, 1865.

The device incorporates 64 thermocouples and generates an emf of 80 millivolts per element. It has an output sufficient to excite 2 electromagnets capable of lifting 105 pounds each.

1263. MARRISON, W. A. **Novel sources of electric power.** *Bell Lab. Rec.* **35**: 406–410, Oct. 1957.

Includes description of a 25 v., 1·25 w. experimental chrome-*p* constantan TE power generator, pole mounted.

1264. Martin Co. Nuclear Division, Baltimore, Md. **Snap III—thermoelectric generator environmental test,** by L. W. GROSS. 68 p., Aug. 1959. (Rept. P-2101).

The effects of simulated space vehicle vibration, acceleration, and shock on the operation and efficiency of a SNAP-III thermoelectric generator are described. The test specifications were developed by Jet Propulsion Laboratories for the third stage and payload of the Vega vehicle. (*Nuclear Sci. Abs.* **13**: 22631, Dec. 31, 1959).

1265. Martin Co., Nuclear Division, Baltimore, Md. **Snap III—thermoelectric generator environmental test,** by L. W. GROSS and E. J. SCHRAMM, VI. III, 70 p., Jan. 1960. (Rept. P-2101-III).

Effects are described of simulated space vehicle vibration, acceleration and shock on the electrical output and efficiency of a SNAP III thermoelectric generator.

1266. Martin Co. Nuclear Division, Baltimore, Md. **Snap III—thermoelectric generator safe handling procedures,** by T. J. DOBRY, JR. and PAUL GUINN. 18 p., Apr. 1959. (Rept. P-2514).

"A method for the safe handling of the SNAP-III thermoelectric generators is presented. It provides information, regarding shipping regulations, general handling instructions for packing, unpacking, and demonstrating the device, and procedures to follow in an event of an accident. Possible hazards involved in handling the device, and the probability of any of these hazardous incidents occurring while it is being demonstrated, are summarised. Containment of the radioisotope fuel used in the SNAP-III device was assured under rigorous conditions, including short time external thermal temperature excursions to 1600°C, when in the shipping container. The probability of the device encountering such temperatures are remote." (*Nuclear Sci. Abs.* **13**: 22632, Dec. 31, 1959).

1267. Martin Co. Nuclear Division, Baltimore, Md. **Strontium-90 power project quarterly progress report 1.** 62 p., Jan. 1959. (Rept. SR-1672) (Contract AT(30-1)-2281).

"The purpose of the Sr^{90} contact is to design an apparatus capable of converting the radioisotopic decay energy into a useful source of electrical power. The apparatus must have a safe, long, unattended life. Two designs will be produced during the contract study, one for land application, and the other for sea application. A model of the land-based application is being completed. It incorporates strontium boride as the heat element compound and lead telluride thermoelectric materials for conversion of heat into electricity." (*Nuclear Sci. Abs.* **14**: 1638, Jan. 31, 1960).

1268. Martin Co. Nuclear Division, Baltimore, Md. **Strontium 90 power project.** Final Summary Report, Oct. 15, 1958 thru Feb. 29, 1960. 143 p., Mar. 1960. (Rept. SR-1676).

The development of a model of a Strontium-90 fuelled thermoelectric generator is described.

1269. MILNES, H. R. **Thermal generation of electric current.** U.S. Patent 2,215,332, Sept. 17, 1940.

A novel thermocouple and a generator employing it are described. The positive element is Cu (70%), Ag (24%), CuO (6%) and the negative Ag (67%), Cu (33%). Both elements are cylindrical discs $\frac{1}{8}$ inch thick held within a ceramic tube and separated by a nickel rod. Operating temperatures are 300–400°C at the hot junction and 100°C at the cold.

1270. MONCKTON, E. H. C. British Patent 3509, Oct. 12, 1874.

Direct or reflected heat is used to heat thermoelectric batteries. Reflectors or lenses for concentrating the heat are mounted on movable frames.

1271. Monsanto Chemical Co. Mound Laboratory, Miamisburg, Ohio. **The mound laboratory thermal battery: some practical considerations,** by J. W. HEYD and K. C. JORDAN. 8 p., Dec. 1, 1954. (Rpt. CF-54-12-1) (Contract AT-33-1-gen-53).

Design considerations, properties, and applications of the thermal battery are discussed. The thermal battery utilises thermocouples as voltage sources, one junction of a thermocouple being heated by a radioactive source. Batteries can probably be constructed with open circuit voltages up to 1·9 v and power outputs up to 24 w. The radioactive isotopes that most nearly meet ideal requirements for the thermal battery are Po^{210} and Sr^{90}.

1272. Monsanto Chemical Co. Mound Laboratory, Miamisburg, Ohio. **Thermal batteries using polonium-210,** by K. C. JORDAN and J. H. BIRDEN. 17 p., June 2, 1954. (Rpt. 984) (Contract AT-33-1-gen-53).

The general theory of thermal batteries of the thermopile type is developed, and this theory is applied to the design of batteries powered by Po^{210} heat sources. The physical characteristics, performance and fabrication of two experimental batteries with 57 and 146 curies, respectively, of Po^{210} are described. Maximum electrical power delivered to a load was 0·1 and 0·2 percent of the power developed as heat by the polonium. The work capacity of the thermal batteries is 1·8 and 9·2 times, respectively, as that of a commerical mercury battery (RM4Z), and the weight is 30% less.

1273. Monsanto Chemical Co. Mound Laboratory, Miamisburg, Ohio. **Nuclear battery—thermocouple type,** by B. C. BLANKE. 14 p., illus., Sept. 30, 1957. (Rpt. CF-57-10-31) (Quart. Rpt. 3) (Contract R-50-799965-sc-01-91).

A second thermoelectric generator consisting of unitised rings of thermopiles was designed and constructed. Three and four rings were assembled into generators and tested. A maximum efficiency of 0·67% was obtained. At a $\triangle T$ of 400°C, an efficiency of 0·56% was obtained; the theoretical maximum for the materials used is 0·83%.

1274. Monsanto Chemical Co. Mound Laboratory, Miamisburg, Ohio. **Nuclear battery—thermocouple type** by B. C. BLANKE. 41 p., Dec. 31, 1958. (Rpt. CF-58-1-40) (Quart. Rpt. 4) (Contract R-50-799965-sc-01-91).

A study has been made and a series of general equations have been derived for the theory of the thermoelectric generator. All equations are presented. The design of a new thermoelectric generator is also presented,

1275. Monsanto Chemical Co. Mound Laboratory, Miamisburg, Ohio. **Nuclear battery—thermocouple type,** by B. C. BLANKE. 29 p., Mar. 31, 1958. (Rpt. CF-58-4-49) (Quart. Rpt. 5) (Contract R-50-799965-sc-01-91).

A third thermoelectric generator has been constructed and tested. Specifications for batteries having outputs of over six volts at power levels of 30, 50 and 1000 milliwatts at the end of six months have been made. An attempt was made to verify experimentally the theoretical equations of the Thomson and Peltier effects.

1276. Monsanto Chemical Co. Mound Laboratory, Miamisburg, Ohio. **Nuclear battery—thermocouple type,** by B. C. BLANKE, n.p., June 30, 1958. (Rpt. CF-58-7-19) (Quart. Rpt. 6) (Contract R-50-799965-sc-01-91).

A thermoelectric generator having independent outputs of 1·2 and 4·8 volts at more than 50 milliwatts after six months' service has been constructed and tested using a mock Po-210 heat source with an initial thermal power of 37 watts.

1277. **New generator uses idle atomic wastes: snap III.** *Sci. News Ltr.* **75**: 180, Mar. 21, 1959.

A new five-pound thermoelectric generator, fueled with the radioisotope polonium-210, is expected to "open the door" to unlimited practical usage of waste atomic products now lying idle in safe storage.

The unit is known as SNAP III (System for Nuclear Auxiliary Power).

1278. **A new thermoelectric couple.** *Elec. World.* **38**: 786, 1901.

A method of thermocouple construction invented by Hermite and Cooper is described. The elements are copper and copper sulfide. An emf of 0·2 to 0·3 volt per thermocouple is generated. U.S. Patent 685,741 describes this device. The contact between the elements is supposed to be indestructible to heat.

1279. NINGARD, E. R. and BANKS, H. O. **Electrical generation by direct conversion using isotopes.** *Nuclear Sci. & Eng.* **2**: 151–152, June 1959.

Isotope-powered generators present an attractive method of converting decay heat of radioisotopes into useful electric power. Strontium-90 and lead telluride have been chosen for the power sources and thermoelectric materials. Two studies are reported; one covering a 100W design for land or sea application and the other a parametric study of space power applications for optimisation of conditions. To provide 2000 watts of thermal power, 15 kg of Sr^{90} will be employed as as trontium titanate-chromium cermet. The present design consists of seven strontium titanate cylinders with cladding placed in a circular arrangement in a cylindrical block, which serves as the heat source.

1280. NOLAN, R. M. **Sun to cool spaceship electronic components.** *Missiles and Rockets* (News and Bus. ed.). **4**: 39, 41, illus., Oct. 13, 1958.

Refers to statements by M. B. Grier, Nortronics Project Engineer, whose report of work in progress indicates that it is possible to construct a thermoelectric solar converter which is comparable in efficiency with the silicon solar cell under free space conditions. The thermoelectric converters could be used with concentrators to increase their efficiency resulting in increased utilisation of power from the sun.

1281. PARFENOV, V. A. **A thermoelectronic generator.** *Nauka i Zhizn.* **26**: 69, 1959.

In Russian.

"A description of a thermoelectric generator for artificial satellites for the earth and moon published in the western press is described. The project features direct conversion of thermal power into electric energy. The generator consists of 2 metal plates separated by only several thousandths of a mm and built into a vacuum tube. One plate is heated to the temperature of about 1,200°, the other to 500°C. The electrons travel from the hot to the cooler plate. Connected up by a conductor, electric current can be thus produced. Thermal energy for the generator will be supplied either by an atomic reactor or by the sun." *Nuclear Sci. Abs.* **14**: 1660, Jan. 31, 1960.

1282. PEARSON, W. B. **Resistance and thermoelectric measurements of cold-worked copper and the resistance minimum at low temperatures.** *Phys. Rev.* **97**: 666–669, figs., Feb. 1, 1955.

Measurements of the change of residual ratio of copper as a function of the percentage reduction in cross-sectional area by cold-working in liquid helium, liquid nitrogen or at room temperature and subsequent ageing treatments show (1) relative change of the ratio during recovery between 77°K and room temperature to that accompanying recovery and recrystallisation at higher temperature; (2) that there appears to be no recovery process taking place below 77°K; (3) that specimens cold-worked in liquid helium or nitrogen and aged at room temperature have a higher residual resistance ratio than specimens both cold-worked and aged at room temperature.

It is found that the thermoelectric force of copper specimens cold-worked at room temperature or liquid helium is positive relative to annealed copper in the range 4–40°K (taking 4°K as zero). The measurements are discussed in relation to the origin of the electrical resistance minimum which is found in copper at 10-14°K.

1283. **Propose nuclear batteries.** *Sci. News Ltr.* **73**: 338, May 31, 1958.

In a summary of remarks on the use and advantages of nuclear batteries for space vehicles, Harold Zahl mentioned developments at the U.S. Army Signal Engineering Laboratory, Fort Monmouth, N.J. The nuclear batteries being developed act as thermoelectric converters. Radiation energy from an isotope is used to produce heat and then to convert the heat with thermocouples into electrical power.

1284. **Radioactive heat to electricity.** *Chem. and Eng. News.* **32**: 4183–4184, Oct. 18, 1954.

Brief description of an atomic battery, developed by Monsanto Chemical Company's Mound Laboratory. It uses the heat from radioactivity to produce electrical energy.

1285. REED, C. J. **Thermoelectric batteries.** *Elec. World.* **29**: 565, 1897.

Various types of thermoelectric generators are summarised.

1286. STINEMAN, R. W. **Optimum reflector-absorber geometry for a solar generator.** *Appl. & Indus.*; **45**: 332–337, Nov. 1959.

As an initial step toward the eventual realisation of a completely static system for converting solar radiation to electric power, the analysis and testing of a laboratory thermoelectric generator has been undertaken. An essential part of the overall system is the combination of reflector and absorber used to collect and concentrate the solar radiation. This paper deals with the geometrical optimisation of the reflector and absorber.

1287. TELKES, MARIA. **Solar thermoelectric generators.** *J. Appl. Phys.* **25**: 765–777, June 1954.

Physical characteristics, TE power, resistivity, thermal conductivity, and temperature differences between hot and cold junctions determine efficiences of thermocouple materials Data have been determined for Chromel *P* constantan. Bi alloys, and ZnSb containing small amounts of added

metals. Using flat-plate collectors with 2 glass panes, efficiency of 0·63% was obtained with the ZnSb alloys in combination with a magnetic Bi alloy. Calculations indicate that the efficiency may be increased to 1·05% by using 4 panes of low-reflection characteristics. With concentrating lenses, efficiency of the 2 pane generator was increased to 3·35%. The maximum allowable cost of TE generators has been evaluated by comparison with present methods of electric power generation.

1288. TELKES, MARIA. **Thermoelectric couple.** U.S. Patent 2,229,481 and 2,229,482, Jan. 21, 1941.

A thermocouple having a positive element of zinc-antimony, and a negative element of copper-nickel, is claimed to give a useful efficiency of 4 to 6 per cent when converting heat into electrical energy.

1289. **Thermoelectric generator drives propeller.** *Aviat. Wk.* **70**: 35, illus., Jan. 26, 1959.

Illustration of a radioisotope thermoelectric generator, designated SNAP III, developed by the Martin Co. in conjunction with the Minnesota Mining & Manufacturing Co.

1290. **Thermoelectric generator with nuclear battery.** *Prod. Eng.* **29**: 5, illus., Aug. 11, 1958.

Includes illustration of novel power source designed by Monsanto engineers at the AEC'S Mound Laboratory.

1291. **Thermoelectric generators have 6% efficiency.** *Missiles and Rockets*, **5**: 25, Jan. 19, 1959.

Brief announcement of development by Minnesota Mining and Manufacturing Co. of generators which use heat applied to semiconducting materials. One of the generators is a five-watt unit, about the size of a quart fruit jar, intended for use with an isotope heat source.

1292. **Thermoelectric generator for outer space.** *Westinghouse Engr.* **19**: 187–188, illus., Nov. 1959.

A model of a solar-powered thermoelectric generator indicates the system is a practical source of electrical power in space. The concave mirror concentrates the sun's rays on the cylindrically shaped generator.

1293. **Thermoelectricity moves up: 100-watt thermoelectric generator for air force.** *Chem. & Eng. News*, **37**: 36, June 29, 1959.

Gives some details of a new class of generator built by Westinghouse and dubbed the TAP-100 (Terrestrial Auxiliary Power, 100 watts). It operates at a temperature of 850°F. and uses a propane flame as the heat source, although it is not limited to gas flames.

1294. **Thermoelectron Engine.** *Electromech· Design.* **2**: 27–28, Apr. 1958.

Atomic heat is converted directly to electricity without moving parts.

1295. WALL, T. F. **The generation of electricity direct from heat.** *Elec. Rev.* **101**: 847–849, 1927.

Experimental data are presented leading to the opinion that the maximum obtainable useful efficiency of a coke-fired thermoelectric generator is four percent. The efficiency of a gas-fired generator is much lower. An experimental ring of 22 couples of copper and constantan delivered 13·7 watts (25 amperes of 0·55 volts) 1 large gas-fired generator comprising thermocouples of iron and constantan delivered only 1·54 watts (0·88 ampere at 1·75 volts) with an efficiency of 0·04 percent.

1296. WATKINS, F. **On thermoelectricity.** *Phil. Mag.* **3**: 304–307, 1837.

The thermopile is constructed of bismuth and antimony and comprises 30 elements 1·5 inches square and 0·125 inch thick. It produces sufficient power to energise an electromagnet which can support a 98-pound weight.

1297. WEBB, H. W. **Thermoelectric generator.** U.S. Patent 1,234,515, Jly. 24, 1917.

The iron and copper-nickel elements of the device are arranged radially around a central compartment through which hot gases flow. A water jacket contains the cooling medium for the outer junctions. The generator is adapted for use on exhaust ports of internal combustion engines.

1298. WEBB, H. W. **Thermoelectric generator.** U.S. Patent 1,242,499, Oct. 9, 1917.

A welded junction iron and copper-nickel thermocouple of the generator protrude through a cylindrical refractory wall. The device is particularly adapted to utilisation of the waste heat of internal combustion engines.

1299. WEIGAND, M. W. **Method of fabricating thermoelectric elements.** U.S. Patent 2,280,137, Apr. 21, 1942.

A generator has wedge-shaped elements of antimony-zinc and strip elements of copper-nickel. A kerosene burner heats 150 hot junctions at 800°C. Air convection maintains the cool junctions at 200°C.; 2 amperes at 8 volts, or 1 ampere at 10 volts is produced.

1300. Westinghouse Research Laboratories, Pittsburgh, Pa. **Thermoelectricity. 22** p., figs., Aug. 31, 1958. (Prog. Rept. 7) (Contract Nobs 72361) (AD-217 227).

Includes Research Report 431FD282-R, Optimisation of a Conventional-Fuel-Fired Thermoelectric Generator, by B. W. Swanson and E. V. Somers.

This report describes conditions in a flame duct which insure maximum extraction of heat from the fuel to generate electric power.

1301. WILLIAMS, J. S. British Patent 700, Feb. 13, 1882.

A thermoelectric generator is enclosed in a glass case and heated by the sun's rays.

APPLICATIONS

(Heat Pumps)

Refrigeration temperature control

1302. ANDREW;, F. W. **Thermoelectric apparatus.** U.S. Patent 1,506,962, Sept. 2, 1924.

The device comprises elements of antimony and bismuth enclosed in tubes. Notches in the tubes permit the cores to make contact. The patent is assigned to the Superior Refrigerating Company, Wapakonota, Ohio.

1303. Bureau of Ships, Washington, D.C. **Thermoelectric air conditioning and refrigeration (Peltier effect) for submarines.** 10 p., n.d.

Describes project the purpose of which is to obtain air conditioning and refrigeration systems for submarines which have no significant noise output.

1304. Carrier Corp., Research and Development Division, Syracuse, N.Y. **Thermoelectric air conditioning systems for submarines.** Progress Report, 2 November—31 December, 1959. 8 p., 1959. (Contract Nobs-77112).

This is the first progress report on a contract for designing a system suitable for integration into a submarine of the SS(N) 593 class.

1305. **Cool, real cool.** *Electron. Tech.* **37**: 68–71, figs., Feb. 1960.

Thermoelectric cooling.

1306. **Competitive thermoelectric heating and cooling.** *Chem. Wk.* **85**: 28, Oct. 31, 1959.

"Devices should be available by 1965, according to industry spokesman. They exhibited their wares at a seminar in Washington sponsored by Whirlpool Corp.

"These systems use electricity directly for heating or cooling thus eliminating all movable parts in refrigerators. A food compartment for aircraft, for example, would hold frozen food at proper temperatures until a switch was thrown converting the refrigerator into an oven, which would cook the food. Radiant heat panels that could either heat or cool a room were displayed.

"High materials cost and the need for direct current are holding up marketing of thermoelectric appliances. The Soviets are reported to be at about the same stage of development as is the U.S." Entire item quoted.

1307. DANIELSON, W. R. **Temperature-controlled chamber using thermoelectric cooling.** *Refrig. Eng.* **67**: 30–33, illus., Feb. 1959.

Thermoelectric cooling requires in materials a figure of merit of 8 to 10 $\times$ 10^{-3} K^{-1} for practical use, today's materials offer only 2 to 2½. The type of application described in this paper is more in the class of a scientific instrument than an appliance. It does, however, demonstrate potentials in a field where thermoelectric cooling is practical today with the materials and performances available.

1308. EICHHORN, R. L. **Thermoelectric refrigeration.** *Refrig. Eng.* **66**: 31–35, June 1958. (First of several articles).

Deals mathematically with the Peltier effect.

Facts and formulas which refrigerating engineers can use in considering the application of a thermoelectric refrigerating system incorporating semiconductor thermoelements to a practical system are presented. Formulas for determining the refrigerating capacity, power requirements and coefficient of performance of a thermoelectric device are derived. The important properties of a material for thermoelectric refrigeration (thermoelectric power, thermal conductivity, and electrical resistivity) are used to determine a figure of merit for the material. Formulas for the use of the thermoelectric principle on a heating cycle are also presented.

1309. **Electronic refrigeration.** *Westinghouse Engr.* **18**: 190–192, Nov. 1958.

A hostess cart with both refrigeration and oven compartments and two models of a baby bottle cooler-warmer are briefly described and illustrated. Each of these products utilises the Peltier effect in semiconductor junctions.

1310. ELLIS, G. B. **Thermoelectric generator designs.** *Elec. Eng.* **67**: 657–660, diags., Jly. 1948.

During the recent war, characteristics such as extreme portability and low maintenance inspired renewed interest in the thermoelectric generator as a portable power supply. This article considers the thermoelectric effect in the conversion of heat to electric energy as the last of a series of articles reviewing the various known and tried methods of producing electric power in the light of present-day knowledge. With its completion, the entire series is scheduled to be made available in pamphlet form.

1311. GOLDSMID, H. J. and HILBOURNE, R. A. **Transistor operation aided by thermoelectric refrigeration.** *Brit. Comm. & Electron.* **7**: 26–30, figs., Jan. 1960.

At present the continuous operation of germanium transistors above a temperature in the region of 100°C is impossible. They could only be used at higher ambient temperatures if some means of refrigeration were provided. In this case, cooling by means of the Peltier effect should prove more convenient than any other form of refrigeration. Silicon transistors are generally inferior to germanium transistors for high-frequency operation but they have the advantage of an upper temperature limit of about 200°C. For use at still higher

temperatures it would be necessary to employ different semiconductor materlas, or alternatively to refrigerate silicon devices. Again, thermoelectric refrigeration could be employed.

In addition, thermoelectric thermostats might be useful in controlling the temperature of transistors and associated components in circuits which are sensitive to temperature changes.

1312. GOLUBYATNIKOV, N. G. **Preservation of milk quality by means of semiconductors. (Thermoelectric refrigerator and heater).** *LLU Trans. Bull.* p. 28–31, 1959.

Translated from *Vest. Sel'skokh. Nauk.* **10**: 99–103, 1958.

The refrigerator in question comprises a thermoelectric battery of circular high-current thermocouples made of a ternary alloy Te–Bi–Se in the negative branch and a Te–Bi–Sb alloy in the positive branch and connected in series. Thermoelectric cooling is based on the Peltier effect.

1313. HARGENS, C. W. **Semiconductors cool and control density gage.** *Electron.* **31**: 80–81, illus., Dec. 5, 1958.

Portable liquid-density gauge capitalises on Peltier effect by using semiconductor thermoelements to maintain uniform cooling temperatures required for accurate specific gravity measurements. Transistorised circuitry uses differential transformer to determine position of movable core at float end.

1314. HARGENS, C. W. **Thermoelectric refrigeration application.** *Frank. Inst. J.* **266**: 523–525, illus., Dec. 1958.

Describes thermoelectric refrigerator for liquid density instruments and includes a schematic diagram.

1315. HIDA, HAJIME, UEMURA, KIN-ICHI and AOKI, MASAHARU. **Cascading of cooling junctions in thermoelectric refrigeration.** *J. Appl. Phys. (Japan).* **26**: 608–610, Nov. 1957.

By cascading cooling junctions in thermoelectric refrigeration, the temperature decrease of 30 degrees is obtained by two-stage cascade, whereas the maximum cooling attainable with a single junction is 23 degrees.

1316. IMAI, ATSUO, UCHIYAMA, SUSUMU and SAKAKI, YONEICHIRO. **Thermoelectric refrigeration by use of bismuth-tellurium alloys.** *Nagoya Sangyo Kagaku Kenkyujo Kenkyu Kokoku.* no. 10: 26–29, 1957.

Not examined.

"The combination of an n-typeBi_2 Te_3 having thermo-emf of −236 microV/deg., specific resistance of 0·896 ohm. - cm., cross-sectional area of 0·59 cm^2 and length of 1·3 cm with a p-type Bi_2Te_3 having 265 microV/deg., 2·23 ohm. -cm., 0·45 cm^2, and 1·0 cm. can produce a temperature difference of 27·0° with an electric current of 20 amp if 0·1 wt. % I is added to the Bi and Te before alloy preparation." *Chem. Abs.* **52**: 15260, Sept. 25, 1958.

1317. IOFFE, A. F., STIL'BANS, L. S., IORDANISHVILI, E. and FEDEREVICH, N. **Thermoelectric refrigerator.** *Kholod. Tekh.* **33**: 62–63, Mar. 1956.

In Russian.

Translation appears in Infosearch Tech. Lit. Info. Serv. Russian Lit. Survey SEM-1-56, p. 5, 1–5·2.

1318. IORDANISHVII, E. K. and STIL'BANS, L. S. **Thermoelectric microrefrigerators.** *Zhurn. Tekh. Fiz.* **26**: 482–483, Feb. 1956.

In Russian.

A brief preliminary report on experiments with semiconductor elements for refrigerators.

1319. IORDANISHVII, E. K. and STIL'BANS, L. S. **Thermoelectric microrefrigerators.** *Zhurn. Tekh. Fiz.* **26**: 945–957, May 1956.

In Russian.

Translation in *Soviet Phys. Tech. Phys.* **1**: 928–939, 1956; also in Infosearch Tech. Lit. Info. Serv. Russian Lit. Survey SEM-1-56, p. 6·1–6·2.

Experiments on the use of thermoelectric coolers with results pertaining to deep cooling by means of a three-cascade thermobattery, to combined cooling (first cascade, compression cooler, second and third, thermoelectric cooler) and to the temperature control of small volumes.

1320. IORDANISHVILI, E. K. and THALICH, L. G. **A semiconductor thermostat for self-excited oscillators.** *Zhurn. Tekh. Fiz.* **27**: 1215–1218, June 1957.

In Russian.

Trans. in *Soviet Phys. Tech. Phys.* **2**: 1109–1113, Feb. 1958.

An experimental crystal oven for use with a quartz crystal-controlled self-excited transistorised oscillator is described. The oven, whose volume is 100 cm^3 and which utilises the Peltier effect in semiconductor thermoelements to maintain a temperature of 20–30°C inside the chamber when the ambient temperature fluctuates from −60 to + 60°C, is battery operated.

1321. IORDANISHVILI, E. K. and STIL'BANS, L. S. **Thermoelectric microrefrigerators.** *Soviet Phys. Tech. Phys.* **1**: 466, 1956.

Trans. of Russian article in *Zhurn. Tekh. Fiz.* **26**: 482–483, Feb. 1956. See Item 263 in May, 1959 issue.

Trans. also available from L.C. or SLA (See *Tech. Trans.* **2**: 650, Nov. 6, 1959).

1322. KOLENKO, E. A., SHCHERBINA, A. G. and YUR'EV, V. G. **Method of heat removal from semiconductor cooling devices.** *Zhurn. Tekh. Fiz.* **28**: 2543–2545, Nov. 1958.

Trans. in Infosearch Ltd. Russian Lit. Survey SEM-7-59.

One of the possible methods of removing heat from hot junctions of a thermoelectric battery in an isolated system is described. It consists of the use of certain substances with high heat of fusion. Expedients and limitations of selection are pointed out.

1323. KRONSBEIN, J. and HARTSAW, W. O. **Peltier effect.** *Refrig. Eng.* **66**: 31–33, 70, Sept. 1958.

Review of trials with use of Peltier effect in refrigerators; amount of cooling that can be obtained per ampere of current, and voltage required; methods of causing Peltier effect.

1324. LINDENBLAD, N. E. **Thermoelectric heat pumping.** *Elec. Eng.* **77**: 802–806, illus., Sept. 1958.

The thermodynamic principles involved in the area governing heat pump phenomena are set forth. The utility and economics of thermoelectric refrigeration and the reversible features of room temperature control, as based upon the present state of the art, are analysed.

1325. LINDENBLAD, N. E. **Thermoelectric cooling apparatus.** U.S. Patent 2,872,788, to RCA.

Thermocouple element for a heat pump. The element has a pair of bodies of dissimilar thermoelectric material mounted on a plate of conductive material. Members transfer heat between the element and the surrounding air.

1326. LINDENBLAD, N. E. **General considerations in research and development pertaining to thermoelectric devices.** *In* NSIA-ARDC Conference on Molecular Electronics, November 13-14, 1958, Washington, D.C., p. 61–65, Washington, D.C., National Security Industrial Association, 1959.

The principle of thermoelectric power is delineated; conditions under which a material renders a high thermoelectric merit factor is illustrated; and the competitive status of thermoelectrics in the area of refrigeration and air conditioning is discussed.

1327. **Peltier effect: thermoelectric airconditioning and refrigeration.** *BuShips J.* **8**: 36–37, fig., Sept. 1959.

General article, in which the Bu-Ships programme in thermoelectric investigations is outlined.

1328. PLANK, R. **Thermoelectric refrigeration.** *Kältechnik* **10**: 2–10, 1958.

In German.

Author reviews the present state of thermoelectric refrigeration in the fields of research and practical achievement. American, British, French, German and Russian contributions are considered. The use of semiconductors for thermocouples is discussed in detail. The physical properties of the most important semiconductors are mentioned and the influence of impurities is stressed. Several refrigerators and an experimental air-conditioning plant are described.

1329. Radio Corporation of America, Camden, N.J. **Monthly progress letter No. 5.** 3 p., Sept. 1959. (Contract Nobsr–77123).

Thermoelectric refrigeration unit for a submarine air conditioning system.

1330. Radio Corporation of America, Camden, N.J. **The design and evaluation of a prototype thermoelectric refrigeration unit for a submarine air conditioning system.** 11 p., figs., Feb. 1960. (Mon. Prog. Ltr. 9). (Contract Nobsr–77123).

Determination of acceptance tolerances for thermoelectric modules received from suppliers is discussed.

1331. Radio Corporation of America, Camden, N.J. **The design and evaluation of a prototype thermoelectric refrigeration unit for a submarine air conditioning system.** 3 p., Mar. 1960. (Mon. Prog. Ltr. 10). (Contract Nobsr–77123).

A systematic study of the metallographic aspects of the bismuth telluride joints with various solders and techniques is under way. It is reported that very little has been done in this area except for some initial studies by Westinghouse.

1332. Radio Corporation of America, Camden, N.J. **Monthly progress letter No. 6.** 21 p., Oct. 1959 (Contract Nobsr–77123).

Reports progress in an experimental programme of evaluation of thermoelectric couples and modules in connection with the design and development of a thermoelectric refrigeration unit for a submarine air conditioning system.

1333. Radio Corporation of America, Camden, N.J. **Monthly progress letter No. 8.** 4 p., Jan. 1960. (Contract Nobsr–77123).

Measurements were continued on various thermoelectric couples and modules. Results of measurements of some are indicated in a table, p. 2.

1334. Radio Corporation of America, Camden, N.J. **Thermoelectric air conditioner—phase I.** 2 p., Nov. 1959 (Mon. Prog. Ltr. 7). (Contract Nobsr–77123).

Attached to this letter is a report of 10 pages that presents results of an attempt to obtain a convenient general formulation of the optimum performance of a real thermoelectric refrigeration machine in terms of its design parameters.

1335. Radio Corporation of America, Camden, N.J. **Thermoelectric air conditioner for submarines. Final report, phase I.** 165 p., Jan. 15, 1960. (Contract Nobsr–77123).

Design, performance, control, material evaluation and test results.

1336. SCHLEGAL, E. **The prospects of electrical refrigeration.** *Z.f.d. ges. Kälteind.* **40**: 2–5, 1933.

Summarizes Peltier refrigeration and reports that the success of this effect depends upon the availability of thermoelectric materials that have a thermoelectric power of at least 200 microvolts/°C and that have very nearly normal Wiedemann-Franz ratios.

1337. SHILLIDAY, T. S. **Performance of composite peltier junctions of Bi_2Te_3.** *J. Appl. Phys.* **28**: 1035–1042, Sept. 1957.

An experimental Peltier refrigerator utilizing thermoelements of annular configuration has been designed, constructed, and operated. The device has been operated under "no-load" conditions

over a range of power inputs and has exhibited a maximum (delta T) of 49°C. A simple theory relating to the performance of Peltier thermocouples is derived. Experimental performance of the device is shown to agree with theoretical predictions.

1338. SMIROUS, K. and STOURAC, L. **Cooling couples for direct energy conversion based on semiconductor systems.** *Elektrotech. Obzor.* **48**: 210–213, 1959.

In Czechoslovakian.

"Semiconductor thermoelectric cooling is discussed. A number of thermocouples are described, of small dimensions and with an output of up to 6W."—(*Instr. Abs.* **15**: 524, Feb. 1960).

1339. SMIROUS, K. and STOURAC, L. **Semiconducting compounds as materials for the construction of cooling elements based on the Peltier effect.** *Elektrotech Obzor.* **48**: 343–350, 1959.

In Czechoslovakian.

"Derives a relation for the temperature decrease $\triangle T$, and discusses the influence of design parameters, the thermoelectric power, electric and thermal conductivity on $\triangle T_{max}$.

The influence of contact resistance at junctions is separately considered. Investigations into the properties of binary compounds of Bi and Te, or Pb and Te, resulted at the best in $\triangle T \propto 35°C$ theoretically and 14°C experimentally. Much better results were obtained with solid solutions of two binary semiconducting compounds, *e.g.* a couple of n-type (Bi_2Se_3—Bi_2Te_3) and p-type (Sb_2Te_3—Bi_2Te_3) resulted practically in $\triangle T = 33°C$. A photograph of such an element is given." *Sci. Abs.* **62B**: 7218, Dec. 1959.

1340. STAEBLER, A. **A primer of thermoelectric refrigeration.** *ASHRAE J.* **1**: 60–65, Aug. 1959.

Considering five major aspects of thermoelectric refrigeration, this paper first presents the advantages of the system. It includes a nontechnical explanation of the thermoelectric process with analogies to well-known principles of mechanical refrigeration. Moving further in the subject, design and manufacturing problems are discussed, and economic considerations are analyzed.

1341. STILBANS, L. S., IORDANISHVII, E. K. and STAVITSKAYA, T. S. **Thermoelectric cooling.** *Akad. Nauk. SSSR, Ser. Fiz. Dok.* **20**: 81–88, Jan. 1956.

In Russian. Translation in Infosearch Tech. Lit. Info. Serv. Russian Lit. Survey SEM–1–56. p. 2.1–2.9.

A brief account is given of A.F. Ioffe's theory of thermoelectric cooling and of experimental results. Temperature differences up to 70°C have been obtained. Applications being investigated include cooling of components in radio and electronic equipment.

1342. **Thermoelectric cold box.** *Eng.* **209**: 480, Mar. 18, 1960.

Describes and illustrates a cold box incorporating semiconducting thermocouple assembly for cooling by the Peltier effect.

For article on thermoelectric cooling using these principles see *Eng.* **208**: 734–735, Dec. 4, 1959.

1343. **Thermoelectric cooling.** *Electron. Eng.* **31**: 690–692, figs., Nov. 1959.

Theory, importance of semiconductor thermocouples and practical applications are discussed.

1344. **Thermoelectric cooling guide.** *Refrig. Eng.* **66**: 51–76, Sept. 1958.

According to the compilers, the editors of Refrigerating Engineering, "the accompanying references represent a reasonably complete record of what has been reported where in this field."

There are 45 references.

1345. **Thermoelectric power-source development.** *Prod. Eng.* **29**: 5, Sept. 22, 1958.

Spotlights two experimental devices unveiled recently. Nortronics Division of Northrop Aircraft calls its unit a midget refrigerator and hopes to use it to cool infrared detector cells, now kept from overheating by liquid nitrogen. "The thermoelectric device is tiny enough so that it can be incorporated in the same tube that holds the infrared sensor, will drop temperature as much as 90°F (from an ambient temperature of 70°F to below freezing).

"RCA has dubbed its device a heat pump, pointing up the fact that thermoelectric elements can serve for heating as well as cooling, depending on the direction in which the current flows. Like the Northrop unit, RCA's is on a very small scale, designed for instrument use."

1346. **Thermoelectric refrigerator-air conditioner-heater for the navy.** *Westinghouse Engr.* **19**: 187, Nov. 1959.

Briefly describes an experimental three-purpose device to be built to test the suitability of thermoelectricity for air conditioning and refrigeration on ships.

1347. **Thermoelectric transistor cooler.** *Electron* **33**: 74–75, illus., Jan. 15, 1960.

Summary of paper given at 1959 Northeast Electronics Research and Engineering Meeting in Boston by P. E. Gray, R. E. Nelson, and J. Blair entitled Thermoelectric Temperature Control of Electronic Components.

It indicates that wide-range temperature control of dissipative electronic components with semiconductor Peltier cooling is within the existing state of the art. Use of the technique to extend a transistor's dissipation limit is a practical illustration.

1348. Whirlpool Corp., Research Laboratories, St. Joseph, Mich. **Design a specific prototype, including controls, of a thermoelectric refrigerating system for use aboard submarines,** January 28, 1960 to February 27, 1960, 4 p., Mar. 3, 1960. (Prog. Rept. 8). (Contract Nobs–77128).

The electrical resistance of the electrical insulating adhesive between the copper conductor and aluminium heat transfer surfaces is 10^9 ohms at 200 volts for a 1/2 square inch area. Failure of the

anodized film on the heat transfer surfaces at the adhesive joint has retarded assembly of the modules.

1349. Whirlpool Corp., Research Laboratories, St. Joseph, Mich. **Design a specific prototype, including controls, of a thermoelectric refrigerating system for use aboard submarines,** February 28, 1960 to March 27, 1960, 5 p., Apr. 19, 1960. (Prog. Rept. 9). (Contract Nobs–77128).

The first thermoelectric module of 144 couples has been satisfactorily completed.

Smaller modules have been constructed and are being used in an effort to evaluate the thermal advantage of increasing the thickness of the thermal insulation beyond the length of the thermoelement.

1350. Whirlpool Corp., St. Joseph, Mich. **Design study to optimize the application of thermoelectric materials for refrigerated spaces aboard submarines.** August 28, 1959 to September 27, 1959. 16 p., Oct. 7, 1959. (Prog. Rept. 4). (Contract Nobs–77128).

An analysis of the thermoelectric system under high current operation.

1351. Whirlpool Corp., Research Laboratories' St. Joseph, Mich. **Design study to optimize the application of thermoelectric materials to refrigerated spaces aboard submarines,** September 28 to October 27, 1959, by R. L. EICHHORN, Nov. 5, 1959. (Prog. Rept. 5). (Contract Nobs–77128).

An analysis is made of the difference in C.O.P. when the C.O.P. is maximized by finding the optimum length/area or the optimum current. Performance of the system when using Z values of $3{\cdot}0\times10^{-3}$, $3{\cdot}5\times10^{-3}$ and $4{\cdot}0\times10^{-3}$ is established. A cross-section drawing of the proposed thermoelectric module construction is shown.

1352. Whirlpool Corp., St. Joseph, Mich. **Type I Thermoelectric temperature controlled chambers,** by A. F. MARTZ and R. G. SICKERT. Interim Development Report, 1 July to 30 September, 1959. 33 p., illus., Oct. 8, 1959. (Contract Nobsr–77617). (AD–228–662).

A summary is given of the work done in designing a thermoelectric cascade and chamber and in analyzing a control system to result in a type I thermoelectric temperature controlled chamber.

1353. Whirlpool Corp., St. Joseph, Mich. **Type I thermoelectric temperature controlled chambers,** by A. F. MARTZ and A. L. WENNERBERG. Interim Development Report 1 October to 31 December, 1959. 29 p. illus., Jan. 8, 1960. (Contract Nobsr–77617). (AD–231–039).

Research concerns the design of a type I thermoelectric temperature controlled chamber for crystals such that the temperature at the crystals will be maintained at 25°C ± 1°C. A further purpose is to study the feasibility of controlling that temperature to ±0·01°C. Many of the circuits which were investigated for their applicability to the solution of the control problem are discussed sufficiently to show what decisions were made regarding them. These include (a) several types of push-pull circuits for regulating current through the thermoelectric cascade, (b) single ended circuits in which direction of current flow is switched with silicon controlled rectifiers and (c) passive and active networks for approximating proportional plus integral control. The proportional controller which was selected for design is described and the known performance data is given. Calculations from this test data show that the system should be able to control temperature to less than 0·2°C. The results of redesigning the thermoelectric cascade taking advantage of the properties of improved materials now available are given. Photographs of the cascade stages prior to final assembly are included.

1354. WRIGHT, D. A. **Thermoelectric refrigeration.** *New Scientist* **5**: 351–353, figs., Feb. 12, 1959.

A general article on semiconductors and the properties which make them suitable for use in thermoelectric cooling. Some investigations of possible applications are cited.

APPLICATIONS

(Miscellaneous)

1355. California University, School of Medicine, Los Angeles, Calif. **Thermoelectric measurement of cerebral blood flow,** by R. R. SONNENSCHEIN. 16 p., Mar. 1958. (WADC Tech. Rept. 58–60). (Contract AF33(616)–2247).

Regional cerebral blood flow was measured thermoelectrically, utilizing a heated thermistor probe. It was found that blood flow varied independently with arterial pressure and local vasomotion. Tissue oxygen tension was shown to be correlated with blood flow, oxygen saturation by the blood and oxygen utilization by the tissue. A local change in cortical blood flow accompanied spreading cortical depression. During the latter phenomenon, a change in surface pH occurred which was parallel to the changes in surface d.c. potential. It was concluded that the change in pH was intimately related to the mechanism of depression and constituted a major factor in the genesis of the d.c. potential shift.

1356. Callery Chemical Co., Pa. **A chemical thermoelectric borane detector,** by L. J. KUHNS and R. H. FORSYTH. 7 p., illus., July 12, 1955. (Rept. 121). (Contract Nobs–52–1024–C). (AD–138–348).

With slight modifications, the Mine Safety Appliance carbon monoxide detector has been adapted for borane detection. Under ideal conditions, the detector is sensitive to 0·2 ppm pentaborane and 0·4 ppm diborane. Considering the dynamic nature of the analysis, the quantitative results are very good. If refrigeration of the sample air is practical, the chemical thermoelectric detector should prove very useful for borane detection.

1357. DOWNING, W. C. **Discussion on "a precision thermoelectric wattmeter for power and audio frequencies."** (by J. J. HILL). *Inst. Elec. Engrs. Proc.* **106B**: 64, Jan. 1959.

Describes a somewhat different approach than Hill's, used in the design of a thermal convertor manufactured by an American company.

1358. FROOD, D. G. **A note on the use of the titanates as thermoelectric transducers.** *Can. J. Phys.* **32**: 313–317, Apr. 1954.

Approximate calculations for a 75%–25% solid solution of $(Ba–Sr)TiO_3$ indicate that it would not be useful as a thermoelectric transducer. It seems possible that if materials could be produced with high permittivity and high temperature coefficient of permittivity but independent of field strength, a transducer with an efficiency comparable to that of a steam engine could be developed.

1359. FRY, W. J. and DUNN, F. **Precision calibration of ultrasonic fields by thermoelectric probes.** *Inst. Radio. Engrs. Proc.* **45**: 380, Mar. 1957.

Abstract of paper given at IRE convention, New York, March 1957.

"The highly-stable, small, and readily-constructible ultrasonic probe developed and in use at this laboratory for the past five years is discussed from the point of view of construction calibration, operation, and application. This transient-type thermoelectric probe, which is currently being used in a number of other laboratories, yields information concerning the pressure amplitude, particle velocity amplitude, and intensity of the ultrasonic field in which it is placed. If the field characteristics are known, the principle of operation of the probe provides a method for determining the absorption coefficient of minute quantities of materials."

Entire item quoted.

1360. FRY, W. J. **Thermoelectric transducer.** U.S. Patent 2, 919, 356, Nov. 2, 1955.

A thermoelectric transducer comprising a thermal pile; means intermittently short-circuiting the output of said thermal pile; magnetic field-producing means having poles directed towards a movable portion of said thermal pile thereby said movable portion reacts with the field to cause relative motion; and resilient means urging said movable portion in a direction opposite to that produced by the reaction of said movable portion with said field; whereby said movable portion of the thermal pile is caused to vibrate at a frequency corresponding to the rate of operation of the means intermittently short-circuiting the output of said thermal pile. (*U.S. Off. Gaz.* **749**: 1292, Dec. 29, 1959).

1361. GEILUNG, LEONARD. **The thermoelement as a measure of radiation.** *Z. Angew, Phys.* **3**: 467–477, Dec. 1951.

In German.

Thermoelements are now used extensively in infrared work. This paper gives an account of their basic principles and a critical discussion of recent developments in design.

1362. GOL'TSMAN, M. I. **Obizmerenii vlazhnosti vozdukha pri nizkikh otretsatel'nykh temperaturakh. (Humidity measurements of air at low negative temperatures.)** *Problemy Arktiki* **1**: 39–53, 1939.

In Russian.

Two methods are presented for accurate determination of humidity at low temperatures as are experienced at Arctic weather stations. The first method involves elaborate equipment using the mass absorption method. The second method is the thermoelectric psychrometer method giving accuracy within ±5% R.H. at −25°C (at Irkutsk). Both types of equipment are illustrated in detail.

1363. HERMACH, F. L. **The definition and measurement of the time constant and response time of**

thermal converters. *Am. Inst. Elec. Engrs. Trasn.* **77**: 277–283, 1958.

A thermocouple in contact with an electric heater may be used as the active element in an a.c. meter giving an indication on a d.c. current meter or for noise measurement. The change of emf after a step change of heater current is only approximately exponential.

1364. HILL, J. J. **A precision thermoelectric wattmeter for power and audio frequencies.** *Inst. Elec. Engrs. Proc.* **105B**: 61–68, Jan. 1958.

A wattmeter has been constructed in which negative feedback amplifiers are used to supply the currents to two compensated converters. The input signal voltages to the amplifiers are obtained from the external circuit by means of a precision wide-frequency band voltage transformer, a four-terminal non-inductive current shunt and a high-resistance voltage divider. The overall instrument error for all conditions of load and power factor is 0·1% over the frequency range 200 c/s to 10 kc/s, and 0·3% for the range 50 c/s to 30 kc/s.

1365. HOHNE, WERNER. **Ueber die weiterentwicklung des thermoelektrischen feinwindmessers. (On further development of the thermoelectric wind measuring instrument.)** *Z. Meteorol.* **8**: 243–247, July/August, 1954.

In German.

A description of the improved wiring of the thermoelectric anemometer is presented. It is heated by means of an alternating current which can be obtained either from the grid (after transformation to a lower voltage) or from an accumulator. Also the heat current can be held constant to a fraction of one percent.

1366. HORNE, R. A., CROFT, W. J. and SMITH, L. B. **Thermoelectric thermostat for X-ray diffraction.** *Rev. Sci. Instr.* **30**: 1132–1134, Dec. 1959.

Includes an illustrated description of a thermoelectric thermostat and circuit useful in the temperature control of samples during X-ray diffraction measurements.

1367. **Instrument for thermoelectric determination of steel type (PMS-2).** *Dig. Soviet Tech. No.* **7**: 37–38, Oct. 1959. From Priborostroenie 8–1959, p. 27.

The instrument reported here measures the thermoelectric voltage produced between the tested material and a hot electrode. Limitation of the method is that it compares only the thermoelectric emf of the specimen to that of the electrode, and cannot answer for possible differences in composition, etc., which do not result in variations of the emf.

1368. IOFFE, A. F. **Two new applications of the Peltier effect.** *Zhurn. Tekh. Fiz.* **26**: 478–482, Feb. 1956.

In Russian.

Translation appears in Infosearch Tech. Lit. Info. Serv. Russian Lit. Survey SEM–1–56, p. 7.1–7.4.

Applications to crystallization and thermal deformations of thermoelements.

1369. KAWATA, S., OMORI, Y. and NISHIMURA, K. **Characteristics of a thermocouple anemometer.** *Kyoto Univ. Fac. Eng. Mem.* **14**: 12–20, Jan. 1952.

"The construction, method of calibration and results of tests of nichrome hot-wire chromel-alumel thermocouple anemometers are described. Two forms of apparatus, one sucking in air by a vacuum pump for horizontal air streams of speeds less than 90 cm/sec. and the other using a propeller for 1–8 m/sec, were used. The results are shown graphically and discussed in relation to the formula $i^2=kE(A+Bv1/2)$ where i is the heater current, E is the emf produced in the thermocouple and v the air-stream speed." *Sci. Abs.* **55A**: 5600, 1952.

1370. KEINATH, G. **Thermoelements.** *Arch. Tech. Messen* **2**: T156, 1932.

In German.

The thermoelectromotive force of various thermocouples is tabulated. A bibliography is appended.

1371. KELEN, ANDREAS and SWEDBERG, PER. **The thermoelectric transistor. A possible battery-less amplifying semiconductor device.** *Appl. Sci. Res.* **6B**: 369–378, 1957.

Criteria are derived for the choice of material, geometrical shape, and heat flow through an amplifying device.

1372. KOLENKO, E. A. **Vacuum trap with thermoelectric cooling.** *Akad. Nauk. SSSR. Vestnik* **27**: 50–52, 1957.

In Russian. Translation in Infosearch Tech. Lit. Info. Serv. Russian Lit. Survey SEM–4–57, p. 9.1–9.2.

Main part of the trap is the semiconductor thermoelectric battery which cools the condensing surface to about -30°C.

1373. KOLOMOETS, N. V., STARNZAS, M. S., STIL'BANS, L. S. and FATEEV, N. P. **Measurement of air humidity using semiconductor thermoelements.** *Zhurn. Tekh. Fiz.* **26**: 686–692, 1956.

In Russian. Translation in Infosearch Tech. Lit. Info. Serv. Russian Lit. Survey SEM–1–56, p. 8.1–8.7.

Describes a novel design of an automatic condensation hygrometer employing a semiconductor thermoelement for cooling.

1374. LAUTZ, G. **Thermoelektrische temperaturstabilisierung elektrischer schaltelemente. (Thermoelectric temperature stabilization of electric switching elements.)** *ETZ.* **80**: 741–745, Nov. 1, 1959.

In German.

"The use of semiconductors in electrical engineering is often made difficult by the pronounced sensitivity of these switching elements to temperature. The article reports on the use of the Peltier effect in order to avoid temperature rises

which might cause damage as well as for the production of constant temperatures. After a description of the basic thermoelectric phenomena and their interrelation, the selection of suitable materials and the design of Peltier elements is explained." *Battelle Tech. Rev.* **9**: 2931, Mar. 1960.

1375. LION, K. S. **Instrumentation in scientific research. Electrical input transducers.** 324 p., figs., New York, McGraw-Hill, 1959.

Thermoelectric transducers (thermoelements or thermocouples). p. 167–174.

1376. LITTLE, G. M. **Thermoelectric cell and making the same.** U.S. Patent 1,638,943, Aug. 16, 1927.

The thermocell has copper and zinc elements sprayed (by the Schoop process) on an insulating base. It is designed for use with radio receivers.

1377. LUGOVSKAIA, M. A. and POKROVSKAIA, I. A. **Pogreshnosti poverki termoelektricheskikh aktinometrov i piranometrov. (Correction of errors of thermoelectrical actinometers and pyranometers.)** *Leningrad, Glavniaia Geofiz. Observ. Trudy* **61**: 120–134, illus., 1956.

In Russian.

Authors present a review of various types of errors experienced during tests of instrumental accuracy carried out, both under natural conditions, at Boekovo, and during expeditions to Kamennaia Steppe and to the Dubovskaia runoff station in 1951–1954, and under laboratory conditions on devices of the Central Bureau of Verification. Data are given in extensive tables and graphs.

1378. Massachusetts Institute of Technology, Cambridge, Mass. **Response of thermoelectric radiation detectors,** by W. F. BROWN and others. 31 p., figs., 1954. (Contract Nobsr–39069; Nobs–25391 Task VIII; Nobsr–52497; and Nobsr–64540).

This report gives the measured response and other characteristics of a number of compensated thermoelectric receivers and describes the methods of measurement used.

1379. NAER, V. A. **An experimental investigation of a thermoelectric evaporation apparatus.** *Soviet Phys. Solid State* **1**: 1092–1095, Feb. 1960.

A thermoelectric evaporation system was constructed to verify experimentally predictions of performance of a thermoelectric battery. Analysis of experimental and theoretical characteristics shows that thermoelectric evaporation apparatus is much more economical than apparatus employing the usual electric heating (electric distillation apparatus).

1380. NICHKEVICH, O. N. **The measurement of the ultraviolet solar radiation as calories.** *Sel'skokhoz. Akad. Ukrain. Nauch. Trudy* **8**: 461–466, 1956.

In Russian.

"A thermoelectric actionometer is described; by aid of 2 glass filters the light of a wavelength >4000 A is removed. It is possible by changing the glass parts to restrict the range of the instrument to certain parts of the ultraviolet only." *Chem. Abs.* **53**: 3871, Mar. 10, 1959.

1381. PALMER, R. B. J. **A thermoelectric method of comparing intensities of ultrasonic fields in liquids.** *J. Sci. Instr.* **30**: 117–179, June 1953.

A new type of indicator is described dependent upon the rise in temperature of certain materials due to the absorption of ultrasonic radiation incident upon them. Experiments are described in which the behaviour of the indicator is compared with that of a radiation pressure detector. Examples are given of its use.

1382. PIPPARD, A. B. and PULLAN, G. T. **A superconducting galvanometer.** *Camb. Phil. Soc. Proc.* **48**: 188–196, 1952.

A superconducting tangent galvanometer suitable for the measurement of thermoelectric voltages in circuits of resistance about 10^{-7} ohm is described. The inductance has been kept low by the use of only a single turn in each of the deflecting coils, but a high sensitivity has been attained by reducing the controlling field to about 0·01 gauss. The theory of operation of such a galvanometer in circuits of low resistance is discussed; the actual behaviour of the instrument is in satisfactory agreement with the theory. The galvanometer will detect a current of 10^{-5} A corresponding to an emf of 10^{-12}V.

1383. RASCHKE, K. **A sturdy thermoelectric psychrometer for microclimatic measurements.** *Indian Acad. Sci. Proc.* **39A**: 98–107, 1954.

Description of a non-ventilated thermoelectric psychrometer for microclimatic measurements.

1384. SCHLITT, H. **A thermoelectric vacuum gauge.** *Z. Angew. Phys.* **8**: 216–217, 1956.

In German.

Range 10^{-2} to 1 mm Hg. The construction is described and a calibration curve, alongside that of a Pirani gauge, is given. The cold junction is in good thermal contact with the glass envelope of the gauge and the hot junction lies inside a heating coil wound on a glass capillary tube. The emf is approximately 1 mV at atmospheric pressure and 12 mV in vacuo for a heating current of 5 mA.

1385. SHIRAKAWA, Y., OHARA, T. and AMEMIYA, D. **Thermocouples with curved characteristics composed of Fe-al-Cr and Cu-Ni alloys.** *Tohoku Univ. Res. Inst. Sci. Repts.* **11A**: 190–200, June 1959.

The thermo–emf of Fe–Al (~8·2% Al), Fe-Cr (~14·8% Cr), Fe–Al–Cr(~6·2% Al, ~11·4% Cr) and Cu–Ni (~4·9% Ni) alloys was measured in the range from 100 to 800°C. The thermocouple composed of a pair of Cu–1·9%Ni and Fe–6·2% Al–0·94%Cr alloys had an emf that was almost zero from room temperature to 400°C nad then increased with temperature to 5·4 mV at 800°C.

1386. SOMINSKIY, M. S. **Semiconductor thermoelectrical apparatuses.** *Akad. Nauk. SSSR. Vest.* **26**: 14–24, Dec. 1956.

Translation from the Russian prepared by

Liaison Office, Technical Information Center, Wright-Patterson Air Force Base, Ohio. (F–TS–9856/III).

Describes various semiconductor thermoelectric generators and their applications for heating and cooling.

1387. TEMPLETON, I. M. **A superconducting modulator.** *J. Sci. Instr.* **32**: 314–315, illus., Aug. 1955.

A new type of d.c. amplifier for use at liquid helium temperatures is described, which has been constructed primarily for measuring small thermoelectric potentials, particularly of the alkali metals at low temperatures, and also for examination of problems connected with redetermination of the absolute scale of thermoelectric power.

1388. **A thermoelectric flow-measuring device.** *Prod. Eng.* **30**: 39, Dec. 7, 1959.

The device described was designed in Sweden and takes advantage of the fact that the amount of heat conducted away from a heated junction immersed in a fluid is affected by variations in the rate of flow of the fluid. Measuring fluctuations in heat transmission therefore indicates variations in fluid flow.

1389. **Voltage and current generating transducers.** *Electron.* (*Eng.ed.*) **31**: 62–64, illus., July 4, 1958.

Thermoelectric transducers, p. 63.

1390. ZAREMBO, L. K. **Thermoelectrical receivers of ultra-sound.** *Izmeritel. Tekh. No.* **5**: 74–77, Sept./Oct. 1958.

In Russian. Not examined.

"Thermoelectric receivers have been designed so that acoustic energy may be changed into heat energy and the latter measured by thermal or thermoelectrical methods. The receivers are used for measuring the sound intensity in liquids and are known for their non-resonating characteristics. They are unaffected by cavitation and turbulence in the liquid." *Brit. Sci. Instr. Reg. Assoc. Bull.* **13**: 333, Dec. 1958.

1391. ZAREMBO, L. K. **Ultrasonic thermoelectric receivers.** *Meas. Tech.* (*USSR*) **5**: 585–589, Sept./Oct. 1958.

English translation. For original entry see Item 1016, Aug. 1959 issue.

1392. ZIKRILLAEV, F. **Temperaturnyi koeffitsient aktinometricheskikh priborov i metody ego opredeleniia. (The thermal coefficient of actinometric instruments and its determination.)** *Akad. Nauk. Uzbek. SSR. Inst. Mat. i Mek. Meteorol. i Gidrol. Uzbek.* 1955, p. 23–33.

Results of experiments on the Ianishevskii thermoelectric actionometer.

APPLICATIONS

(Thermocouples)

1393. Armour Research Foundation, Chicago, Ill. **The development of high temperature thermocouples,** by GARY STEVEN and W. C. TROY. n.p., illus., Sept. 16, 1948. (Memo. Rept. 9). (NEPA–764–ARM–10).

The W/Ir thermocouple was selected from a number of metal combinations used as being the most likely to meet the requirements of good thermal emf properties and long time stability at 2000°C.

1394. Armour Research Foundation, Chicago, Ill. **The thermoelectric and electromechanical properties of $BaTiO_3$ single crystals with application to the detection and measurement of far infrared radiation,** by G. W. FRANCIS, 85 p., June 1957.

It is shown that when compared with other thermal radiation detectors, both the $BaTiO_3$ crystal and ceramic detectors offer certain advantages. The detectivity varies inversely as the square root of the frequency while for the resistive type bolometer the detectivity varies inversely with the frequency.

1395. Atomic Energy Commission, Oak Ridge, Tenn. **Thermocouple research report for the period 1 November 1956 to 31 October 1957,** by D. L. MCELROY. 87 p., Mar 5, 1958. (Rept. ORNL–2467). (Prog. Rept. 1).

Describes the first year of progress in an investigation of thermoelectric thermometry, with particular reference to Chromel–Alumel type alloys in the range 500–1100°C.

1396. BARBER, C. R. and PEMBERTON, L. H. **Silver-palladium thermocouples.** *J. Sci. Instr.* **32**: 486–487, Dec. 1955.

Includes a table showing typical emf temperature calibration of a silver–palladium thermocouple (Reference junction temperature 0°C.).

1397. BARBER, C. R. **The emf temperature calibration of platinum, 10% rhodium-platinum and platinum, 13% rhodium-platinum thermocouples over the temperature range 0°-1760°C.** *Phys. Soc. Proc.* **63B**: 492–503, July 1950.

Tables are given which are based on the calibration of 12 thermocouples of each kind, 6 from each of 2 manufacturers. The methods of intercomparison between the thermocouples and the various interpolation instruments specified in the International Temperature Scale are described. It is shown that the difference between the new tables and the old are mainly due to changes in the International Temperature Scale, and that the new tables represent the shape of the emf temperature characteristics of the thermocouples of either make sufficiently close to give interpolation between calibration points with accuracy within ±1°C up to 1063°C, ±2°C up to 1500°C and ±3°C above this temperature.

1398. BARRETT, W. F. **Novel thermoelectric phenomena.** *Phil. Mag.* **49**: 309, 1900.

An alloy of iron–nickel–manganese–carbon is used with iron as the thermocouple. The emf and resistance are constant through a wide range of temperature.

1399. BEAKLEY, W. R. **Method for modifying the thermal emf temperature characteristics of Constantan thermocouple wire.** *J. Sci. Instr.* **31**: 259–260, July 1954.

Three-foot lengths of 40 s.w.g. constantin wire were taken from a reel, the sensitivity of which was approximately 0·8μ V/°C greater than the lead wire with which it was to be used. Each length was held horizontally under very slight tension in air in a draught-free enclosure. An alternating current from the mains, controlled by a Variac transformer, was passed through the sample, and a 12-in. length from the middle of the sample was tested against wire from the reel.

1400. BENEL, H. **Effect of the gaseous atmosphere on the thermoelectromotive force of a bimetallic couple massive silver-pure thin copper-massive copper.** *Rev. Fac. Sci. Univ. Istanbul* **22C**: 177–182, 1957.

In French.

The thermo-emf of a bimetallic couple of massive Ag/thin Cu/massive Cu, purified by degassing, depends on the pressure of the gaseous atmosphere enveloping the couple. This behaviour is attributed to an inhomogeneity created by the uneven adsorption and occlusion of gas by the different parts of the couple. The effect of an atmosphere of H at pressures ranging from 0 to 550μ Hg is studied.

1401. BENEL, H. **Influence of a vaporous atmosphere on the thermal electromotive force of a couple consisting of pure solid silver in contact with a thin film of silver.** *Rev. Fac. Sci. Univ. Istanbul* **21C**: 26–33, Jan. 1956.

In French.

The thermal emf of a degasified solid Ag/thin-film Ag couple is a function of the vapor pressure which envelops the couple. This effect is attributed to a supplementary inhomogeneity which arises from unequal adsorption and occlusion of the gas by the branches of the couple. The thermal emf attains a maximum at a thickness of about 33 mμ of the thin-film branch. Important emf variations as a function of thickness were observed between 20 and 47 mμ. The current in the couple travels from the solid Ag to the thin-film Ag by way of the heated junction.

1402. BENEL, H. **The variation of the thermoelectric electromotive force of a monometallic couple, thick silver/massive silver, as a function of the thickness of a copper layer deposited on the**

massive silver branch. *Rev. Fac. Sci. Univ. Istanbul* **22C**: 124–127, 1957.

In French.

For a given temperature, the thermoelectric emf of a monometallic couple such as thick Ag/massive Ag decreases with the deposition of layers of Cu of increasing thicknesses on the massive Ag branch, until a final value is reached for massive thickness of Cu. It has a specific value depending on temperature and thickness of Cu.

1403. BORISOV, YE. **Automatic control and semiconductors.** *Znaniye Sila* **34:** 28–32, August 1959.

Tells of work on semiconductor thermocouples being conducted at the Institute of Powder Metallurgy, Cermets, and Special Alloys of the Academy of Sciences Ukrainian SSSR, located at Kiev.

In Russian.

A thermocouple considered to be of importance consists of boron carbide and silicon carbide which develops an unusually high thermal emf, up to 600 microvolts per degree. This is a transducer which transforms heat into electric energy. At present, installations with a temperature ceiling of 1700° will become available for the work in question. This opens up extensive possibilities as far as generation of electric power by means of semiconductor appliances is concerned. Additional information may be obtained from a lengthy translation appearing in CIA Scientific Information Report, Oct. 23, 1959, p. 40–43. (PB131891–T–32).

1404. BRINTON, R. K. and O'KONSKI, C. T. **A phototube measuring circuit for thermopiles.** *Rev. Sci. Instr.* **24**: 1102–1104, Dec. 1953.

A recording system is described which measures the emf generated by slowly responding linear-type thermopiles. A means is provided for compensating electrically for the zero signal drift so that the thermopile may be used conveniently under rather unstable thermal surroundings.

1405. BRISTOL, W. H. **Thermoelectric couple.** U.S. Patent 1,315,205, Sept. 9, 1919.

A compound thermocouple of 4 elements generates an emf of 4 or 5 times that of a platinum-rhodium thermocouple, and gives a linear temperature versus emf curve. The 4 elements are copper plus 0·5% nickel, nickel plus 10% chromium, nickel plus 2% aluminium, and copper plus 40% nickel.

1406. BROWN, D. A. H., CHASMAR, R. P. and FELLGETT, P. B. **The construction of radiation thermocouples using semiconducting thermoelectric materials.** *J. Sci. Instr.* **30**: 195–199, June 1953.

An investigation is reported of methods of construction of thermocouples of the type described by E. Schwarz. The composition of the thermoelectric materials is discussed. Performance figures for experimental thermocouples are given together with those obtained on commercial couples made by Schwarz.

1407. BROWN, S. L. and SHUDDENMAGEN, L. O. **Thermal electromotive force of iron oxide and copper oxide.** *Phys. Rev.* **5**: 385, 389, 1915.

Experiments on thermocouples with elements of iron oxide and copper oxide are reported.

1408. BUNCH, M. D., POWELL, R. L. and CORRUCINI, R. J. **Thermal emf of some thermometric alloys.** *In* International Conference on Low Temperature Physics and Chemistry. Proceedings. 5th, 1957, p. 484–486, Madison, University of Wisconsin, 1958.

Reports, investigation, primary purpose of which was to establish representative temperature-emf tables for gold–cobalt, constantan and 'normal' silver versus ordinary copper-magnet wire throughout the range 0°K to 300°K.

1409. CAMPAN, TEODOR and ANGHELACHE, D. **O sonda termoelectricia pentru masurarea temperaturilor de suprafata la pereti si alte corpuri. (Thermoelectric device for the measurement of surface temperature and other bodies).** *Iasi. Inst. Polit. Bul.* **4**: 365–370, 1958.

In Rumanian, with German summary, p. 370.

Noted in East European Accessions List (Library of Congress, **9**: 285, Mar. 1960).

1410. CARTER, H. J. **A method of constructing Cu-constantan thermocouples.** *Rev. Sci. Instr.* **19**: 917–918, Dec. 1948.

The junction is at an end-to-end joint, and the wires are held in position by a thin Cu sleeve, above 1 mm long, deposited electrolytically. Wires 0·0025 in. dia. can be used, giving small mass and surface area. The emf obtained is the same as that from soldered or welded junctions.

1411. CHASTON, J. C. **Thermocouple for high temperatures.** *Platinum Metals Rev.* **1**: 20–22, Jan. 1957.

Advantages of 5% rhodium—20% platinum thermocouple for measuring very high temperatures.

1412. COBLENTZ, W. W. **Thermoelectric behavior of tungsten and tantalum.** *Phys. Rev.* **28**: 312, Apr. 1909.

Abstract only of paper presented at meeting of Physical Society, Feb. 27, 1909.

"Further improvement in the construction of thermopiles must come through the reduction of the heat capacity of the junctions."

1413. CORRUCCINI, R. J. and SHENKER, HENRY. **Modified 1913 reference tables for iron-constantan thermocouples.** *J. Res.* **50**: 229–248, May 1953.

Investigation was made of characteristics of typical commercial IC thermocouples to reproduce standard temperature-emf relationship established in 1913. Using calibration of thermocouple that most nearly matched 1913 reference table from 32 to 1400°F a slightly different temperature-emf relationship was derived which is more nearly realizable by commercially available materials.

1414. DAUPHINEE, T. M., MACDONALD, D. K. C. and PEARSON, W. B. **The use of thermocouples**

for measuring temperatures below 70°K. A new type of low temperature thermocouple. *J. Sci. Instr.* **30**: 399–400, Nov. 1953.

The use of thermocouples such as copper-constantan to measure low temperatures (*e.g.* ~10K) may result in considerable uncertainty in the measured temperature. These uncertainties are discussed and a method described for reducing them to ±0·5°. It is shown that thermocouples composed of pure copper against certain dilute copper alloys (*e.g.*, copper + ~0·005 wt. % tin) have particular advantages for measuring temperatures in the range 2–30°K.

1415. DAUPHINEE, T. M. **An apparatus for comparison of thermocouples.** *Can. J. Phys.* **33**: 275–285, June 1955.

This paper describes a semiautomatic apparatus for routine or precision comparisons of thermocouples of the same type in the temperature range 0–1100°C. The couples being compared are welded together at the tips and placed in a tube furnace which is heated at rates varying from 10 to 100°C/min.

1416. DOSCHECK, ANTONY. **Applications of the triboelectric and the thermoelectric effects to the sorting of metals.** *Non-Destructive Test.* **10**: 22–28, Fall 1951.

Describes fundamental principles of the above in elementary terms. Apparatus and procedure are also described. An alloy of 90% Ni and 10% Cr has been found to be electrically "positive" to all of a very large number of various pure metals and alloys. Triboelectric reactions with various types are described.

1417. DUNN, FLOYD and FRY, W. J. **Precision calibration of ultrasonic fields by thermoelectric probes.** *Inst. Radio Engrs. Trans. PGUE*-**5**: 59–65, August 1957.

Transient type, thermoelectric probe yields information concerning the pressure amplitude, particle velocity amplitude, and intensity of the ultrasonic field in which it is placed.

1418. EBINGER, A. **Portable temperature-indicating instruments for connection to thermocouples.** *AEG Mitt.* **42**: 180–184, July/August 1952.

In German.

"Temperature measurement with thermocouples requires for the indication moving-coil instruments with particularly high-voltage-sensitivity. Three laboratory types of indicating instruments, their external design and their electrical properties are described in detail and illustrated.

1419. FORNANDER, S. **Temperature measurements on liquid steel.** Transactions of Instruments and Measurements Conference, 1947 (Stockholm), p. 223–227, 1947.

Early techniques in thermoelectric temperature measurement of liquid steel used lagged couples to reduce thermal shock on immersion, with consequent slow response A Pt/Pt–Ph couple in a vitreous silica sheath may be used unlagged and gives quick readings so that the head need only be immersed for about 15 seconds, short enough to prevent corrosion. Tests show that the accuracy and reproducibility of the results are sufficient, between 50 and 80 determinations being possible before changing the hot junction, according to the type of furnace in use.

1420. FUSCHILLO, NICHOLAS. **A low-temperature scale from 4 to 300°K in terms of a gold-cobalt versus copper thermocouple.** *J. Phys. Chem.* **61**: 644–646, 1957.

A low-temperature scale was obtained by comparing the emf from the Au+2·1 at % Co vs. Cu thermocouple with the temperature values obtained from a constant-volume. He gas thermometer. By paying appropriate attention to the prevention of temperature gradients and to the homogeneity of the alloy, the absolute thermodynamic scale can be realized to between 0·1 and 0·2 from 4° to 10°K and to better than 0·1° above this temperature. The emf's were reproducible within these limits on successive reductions to He temperatures. The use of a composite 3-limb Au–Co vs. Cu vs. constantan thermocouple was described. This thermoelement enables the avoidance of the N temperature fixed point and permits checking one thermocouple against the other two.

1421. FUSCHILLO, N. **Inhomogeneity emfs in thermoelectric thermometers.** *J. Sci. Instr.* **31**: 133–136, Apr. 1954.

A criticism is made of the methods available for selecting metallic wires to be used in the construction of thermoelectric thermometers. Methods are described which increase the reliability, rapidity and convenience of selection tests. Techniques are introduced for the construction of more homogeneous thermocouples, and multi-junction thermoelements from a test cable of the wire under consideration, thus extending the range of application of the thermoelement to the precise measurement of larger temperature differences and the validity of its calibration to more varied conditions. Examples are given of the application of these procedures to the construction of low-temperature copper/constantan thermometers.

1422. General Electric Co., Knolls Atomic Power Laboratory, Schenectady, N.Y. **Thermal electromotive force of uranium, titanium, and zirconium,** by L. L. WYMAN and J. F. BRADLEY. 20 p., 1952. (Rept. 852).

The emf values of U–Pt, Ti–Pt, and Zr–Pt thermocouples were determined from room temperature to 1200° by the use of an automatic recording device. The effects of cold-working, annealing, and thermal cycling on the emf were studied. The characteristics of the Ti–Pt and Zr–Pt couples were similar and the emf results were sensitivive to structural changes and to the ambient atmosphere.

1423. GROMOV, N. P., GOLOVANENKO, S. A. and KASATKIN, N. M. **New thermo-bimetals.** *Vest.*

Elektroprom. No. **8**: 32–33, 1956.

In Russian. Not examined.

"During the last three years, a number of new bimetals for thermoelements, not provided for in GOST 5198–50, has been developed in the Institute for Precision Alloys, TsNIIChZh.

1424. GUETTEL, C. L. **Thermocouple alloys resistant to high-temperature oxidation.** U.S. Patent 2,757,221 (to Driver Harris Co.), July 31, 1956.

The positive element is an alloy containing 18–22 % Cr, rest Ni; the negative element is a Ni alloy containing 2–4% Mn, 1–3% Al, and about 1% Si. When the atmosphere contains gases in which, Cr alloys are subject to "green rot" deterioration 2% Nb can be added to the positive element. The temperature-emf relation is given for the two types of thermocouples from 32 to 2300°F.

1425. HAASE, G. and SCHNEIDER, G. **Experiments on thermocouples made from the iridium/rhenium system.** *Z. Physik* **144**: 256–262, 1956.

In German.

The thermoelectric powers of Ir, Re and of various alloys were measured against W up to 2450°C, 50° higher than previous measurements on metals. It was found that a couple consisting of Ir and an alloy Ir 30%, Re 70% was of practical use in the measurement of temperatures even in a slightly oxidizing atmosphere, a little above 2000°C.

1426. HERMANN, OTTO. **Thermoelectric element.** U.S. Patent 1,575,117, Feb. 9, 1926.

A negative element of Ni (81%)–Mo (17%)–V (2%) and a positive element of Ni (40%)–Cu (60%) generate a high emf. The resistivity of the thermocouple is low.

1427. HERMANN, OTTO. **Thermoelectric element and thermocouple.** U.S. Patent 1,920,559, Aug. 1, 1933.

The thermocouple has a positive element of Cu (55%)–Ni (45%), and a negative element of Sb (60.7%)–Zn (36·3%)–As (3%). It produces an emf of 0·09 volt at 300°C temperature difference.

1428. HEUSINKVELD, W. A. **Measuring temperatures by thermoelectrical methods and optical pyrometers.** *Ing.* **69**: 109–112, Nov. 1957.

In German.

In this communication the International Temperature Scale is briefly summarized. The method of calibrating thermocouples and optical pyrometers is described and the obtainable accuracy is indicated. A method of determining the temperature of an arbitrary radiating surface and the suitability of tungsten strip lamps for use in comparing the calibrations of optical pyrometers are mentioned.

1429. HIRAI, B. and ISHIKAWA, M. **Thermoelectric character of iron-constantan thermocouples.** *Electrotech. Lab., Japan. Bull.* **18**: 280–285, Apr. 1954.

Tables of thermo-emf of many nations are examined, and the thermoelectric characteristics of the iron-constantan thermocouples made in those nations and now used in Japan are determined in order to establish reference tables for iron-constantan thermocouples in the Japanese Industrial Standards. The iron-constantan thermocouple of the 0·75 class of the Japanese Industrial Standards is easily constructed if each wire is selected with consideration of its individual character and the fact that Mn as an impurity causes deviation of emf from the standard.

1430. HUNSINGER, W. **Instrumentation for thermoelectric measurement of temperature for high degree of accuracy, especially for thermal analysis.** *Z. Metallk.* **44**: 261–264, June 1953.

In German.

Description of conventional and improved methods of recording with accuracy a thermocouple signal. Feedback is used over a galvanometer and photocell arrangement. With proper bias, the system can record with great accuracy a temperature varying between two very narrow limits. This permits observation of any sharp changes or other singularities in a temperature-versus-time record. References are made to German commercial instruments.

1431. KAMPE-NEMM, A. A. **The application of a thermoelectric proportional-plus-integral corrective device for improvement of two-position temperature control.** *Automation & Remote Contr.* **19**: 461–463, illus., May 1958.

Translation of Russian article in Abtom. & Telemekh.

An automatic control method which is based on application of a thermoelectric corrective device and combines the properties of two-position and proportional-plus-integral control is treated. The construction of the corrective device is described. Experimental results show that the proposed device permits a substantial improvement of the two-position control process.

1432. KEINATH, G. **Thermoelements.** *Arch. Tech. Messen.* **2**: T10–T11, 1933.

In German.

Various thermocouples are discussed. A bibliography is appended.

1433. KIRSCHNING, H.-J., HOCHSTRATE, E. and RODRIAN, H. **A contribution to temperature measurement in the arch of open-hearth furnaces by thermoelectric methods.** *Arch. Eisenhüttenw.* **28**: 611–614, Oct. 1957.

In German.

The performance of various protective sleeves of ceramic materials for thermocouples used in measuring arch temperatures has been studied. When the diameter of the sleeves is kept small, to prevent the formation of heat stress, the major problem consists in the penetration of the sleeve wall by carbon, which affects the structure of the materials in different ways. BeO was found to be the most suitable material for these sleeves.

1434. KOITZSCH, R. **Ueber den einfluss der**

temperatur der gegenloetstelle bei thermoelektrischen messungen mit elementen aus kupfer-konstantan. (The influence of the temperature of the reference junctions on thermoelectric measurements with copper-constantan elements). *Z. Meteorol.* **6**: 129–132, May 1952.

In German.

A mathematical analysis of the relationship between changes of temperature at the reference junction and the measuring junction and a description of the determination of the constants α and B in the equation showing the relation between emf and temperature difference between reference and measuring junction.

1435. LACHMAN, J. C. **Refractory metal thermocouples.** *Am. Soc. Mech. Engrs. Paper* 59–HT–21, 1959.

Thermoelectric properties of refractory metals were studied with particular attention to rhenium. Pure metal combinations of rhenium/molybdenum, rhenium/tungsten were calibrated to 4,000°F in vacuo, in hydrogen and in inert-gas. Practical application and limitations are discussed.

1436. LACHMAN, J. C. **Calibration of thermocouples to 4000°F.** *Instr. & Contr. Sys.* **32**: 1030–1032, July 1959.

Rhenium-tungsten and rhenium-molybdenum thermocouples were found to have the following advantages: high thermoelectric potential; high thermoelectric power (millivolts per degree); high melting point of all components; chemical stability in neutral or reducing atmospheres; and ductility (for rhenium or rhenium-alloy legs of thermocouples) after temperature cycling. (*Instr. Abs.* **14:** 316, Oct. 1959.).

1437. LODDING, WILLIAM and STURM, EDWARD. **A new method of differential thermal analysis employing multiple thermocouples.** *Am. Mineralogist* **42**: 78–82, 1957.

The emf generated by thermal reactions can be multiplied by placing a number of thermocouples in series. Peak amplitudes in thermograms are increased by a factor directly related to the number of differential couples used.

1438. Massachusetts Institute of Technology, Cambridge, Mass. **A radiation detecting mosaic thermopile.** July 1952–June 1956, by F. C. BAKER; J. L. CUFF; M. E. KREIDER; D. R. STACKPOLE; L. HARRIS. 25 p., figs., Nov. 14, 1956. (Contract Nobsr–52497).

Two mosaic radiation thermopiles, each with a receiving area of ~0·01 square inch, have been constructed and their response to interrupted radiation measured. Each thermopile is composed of twenty compensated thermoelectric units, each unit electrically insulated from the others. Twenty-one electrical leads are brought out from these thermoelectric units to the insulated terminals of a steel case.

1439. MCQUILLAN, M. K. **Some observations on the behaviour of platinum-platinum/rhodium thermocouples at high temperatures.** *J. Sci. Instr.* **26**: 329–331, Oct. 1949.

It has been found that in air more Pt than Rh is lost by preferential oxidation, and in vacuo, by volitilization. Very little metal is lost on heating in H. An explanation of those effects hitherto explained by loss of Rh has been suggested. The effect of heating Pt wires in a reducing atmosphere in the presence of refractory materials other than those containing Si has also been investigated. C, beryllia and alumina have been found to have no contaminating effect. No appreciable change in the thermal emf developed at 950°C has been observed in thermocouples heated in H for 12 hours at 1600°C.

1440. METCALFE, A. G. **The use of platinum thermocouples in vacuo at high temperatures.** *Brit. J. Appl. Phys.* **1**: 256–258, Oct. 1950.

In the course of thermal analysis on Co base alloys in vacuo with Pt–Pt 13% Rh thermocouples it has been found that the emf developed at any temperature gradually falls. The principal cause of this is believed to be the transfer of Rh to the Pt wire via the vapour phase. It has been shown that this effect can be reduced considerably by the use of a Pt 1% Rh wire in place of the Pt wire.

1441. MIKHAILOV, N. S. **High-temperature thermocouple.** U.S.S.R. Patent 105,227, Mar. 25, 1957.

A semiconductor thermocouple for measuring temperatures up to 1800° is made of pressed and sintered semiconductors, e.g. one thermoelectrode of TiC and the other of SiC. Of these, the more heat-resistant TiC is made in the form of a tube enclosing the rod-shaped SiC electrode.

1442. **Mineral insulated thermocouples.** *Eng.* **187**: 717, May 29, 1959.

A thermocouple made by British Insulated Callender Cables is described. The thermoelectric conductors (nickel–chromium for the positive and nickel-aluminium for the negative) are embedded in highly compressed magnesium oxide insulant and then completely encased in a seamless, circular, stainless-steel sheath. Thermocouples of all sizes down to 0·060 in. diameter can be supplied with an insulating junction. (*Instr. Abs.* **14**: 265, Aug. 1959).

1443. MOLL, W. J. H. and BURGER, H. C. **A new vacuum thermoelement.** *Phil. Mag.* **50**: 618–624, 1925.

Experiments with a thermocouple of manganin and constantan are described and the sensitivity is discussed.

1444. MUKHINA, E. G. **Ob izmerenii temperatury rastenii termoelektricheskim plastinchatym priemnikom. (Measurement of plant temperature by means of a thermoelectric plate receiver).** *Moscow Tsentral. Inst. Prognozov. Trudy.* **37**: 32–40, 1954.

In Russian.

"The various advantages in measuring the temperature within a plant thermoelectrically by using temperature receivers, either in the form of

plates or needles, are discussed. The author describes a thermoelectric device for measuring temperature of plants. Data are presented on the temperature of a leaf measured with a needle or plate-like receiver in the presence of radiation, temperature of a plant measured with a plate receiver in the presence of artificial radiation, temperature of fruits and stalks, of soils, etc."

Meteor. Abs. Bib. **9**: 1132, Sept. 1958.

1445. National Advisory Committee for Aeronautics, Washington, D.C. **Some effects of exposure to exhaust-gas streams on emittance and thermoelectric power of bare-wire platinum rhodium-platinum thermocouples.** 30 p., Aug. 1954. (Tech. Note 3253).

Exposure to exhaust-gas streams from the combustion of propane, 72-octane gasoline, and MIL-F-5624A grade JP-4 fuel caused negligible changes of thermoelectric power of unshielded platinum 13% rhodium-platinum thermocouples. The increase in the effective total hemispherical emittance during exposure accounted for the increase of irradiation error, the source of apparent error between the test thermocouples and the working standards. Authors suggest that, in applications where long time reproducibility of the thermocouple is desired, pre-exposure to operating conditions can establish a condition of stable effective emittance.

1446. National Advisory Committee for Aeronautics, Washington, D.C. **A thermocouple subcarrier oscillator for telemetering temperatures from pilotless aircraft,** by C. L. Fricke. 50 p., Dec. 1957. (Tech. Note 4128).

An oscillator is described which, in conjunction with the NACA telemetering system, gives a satisfactory method for telemetering temperatures. The design uses a diode-bridge modulator in a phase-shift oscillator; the thermocouple voltage is changed to alternating current and used to shift the phase and hence to change the frequency of oscillation. This method results in an oscillator having a small size, low microphonics, high input resistance, and satisfactory stability if a switch is used to commutate calibration voltages along with the pickups.

1447. Noggle, T. S., Blewitt, T. H., Coltman, R. R. and Klabunde, C. E. **Thermo-emf vacuum-seal for electrical lead wires.** *Rev. Sci. Instr.* **28**: 464, 1957.

Lead wires used in conjunction with low-temperature pile irradiations were satisfactorily potted in cold setting thermoplastic to give a thermo-emf-free vacuum-seal.

1448. Ohl, R. S. **Thermoelectric system.** U.S. Patent 2,407,678, Sept. 17, 1946.

The thermocouple comprises one element of n-type silicon and one element of p-type silicon. Both types are prepared by fusion of 99% pure silicon to obtain suitable ingots with varying cross sectional structure. The thermocouple produces 0·078 volt at 100°C temperature difference. It is used to measure radiant energy. The patent is assigned to the Bell Telephone Laboratory.

1449. Ornatskii, P. P. **Application of thermoelectric instruments at very low frequencies.** *Meas. Tech. (USSR).* **5**: 549–552, Sept./Oct. 1958.

English version of Russian article appearing in *Izmereitel'naia Tekhnika.* **5**: 44–46, Sept./Oct. 1958.

Translation also appears in *Electronics Express.* **1**: 38, Dec. 1958.

It is established that thermocouple instruments provide with sufficient accuracy and a small deflection alternating component, the possibility of measuring effective values of the current and voltage at very-low frequencies and therefore can be recommended as standard instruments as well.

1450. Perry, E. R. **Platinum-platinum-rhodium thermocouples for measuring temperatures in the foundry.** *Fonderie Belge*, **29**: 201–205, Sept. 1959.

In French.

"A detailed account of the thermoelectric pyrometer, materials suitable for construction of thermocouples, methods of protecting them during use, and maintenance procedures." (*Brit. Cast Iron Res. Assoc. Bull. Foundry Abs.* **14**: 1016, Nov. 1959).

1451. Powell, R. L. and Bunch, M. D. **The thermal emf of several thermometric alloys.** *Inst. Intern. Froid, Bull.*, p. 129–135, 1958.

Reprinted by National Bureau of Standards, Cryogenic Engineering Laboratory.

Thermoelectric powers for gold-cobalt and constantan vs. copper thermocouples are given.

1452. Reid, R. J. and Gross, W. M. **Thermocouple element.** U.S. Patent 2,916,537 (to General Dynamics Corp.), Dec. 27, 1956.

A thermocouple element having fast response time to rapidly changing temperatures conducted thereto by air masses of high velocity, said element comprising a junction formed by two dissimilar materials in the thermoelectric series, leads extending from each of said materials, and a support for supporting said materials in a Mach 1 air stream, said support providing continuous support throughout the length of said materials, said support being extremely thin under said junction to reduce heat conduction losses thereto and relatively thicker at the part where the leads extend from said materials to thereby provide a raised under-surface for air circulation thereunder.

1453. Roberts, C. C. and Vogelsand, C. A. **Thermoelectric pyrometry.** *Paper Indus.* **31**: 459–460, diags., Jly. 1949.

Several fundamental thermocouple phenomena are discussed and interpreted from the standpoints of their practical application.

1454. Roeser, W. F. **Thermoelectric thermometry.** *J. Appl. Phys.* **11**: 388–407, 1940.

Fundamental laws and theories of thermoelectric phenomena and their historical developments and application to temperature measurement are

considered in detail. Practical thermoelectric thermometry is discussed.

1455. ROESER, W. F. and DAHL, A.I. **Reference tables for iron-constantan and copper-constantan thermocouples.** *J. Res.* **20**: 337–355, tables Mar 1938. (Res. Paper 1080).

Tables have been prepared giving corresponding values of temperature and thermal electromotive force at various temperatures from − 200° to 1000°C, for iron-constantan thermocouples. Similar tables from −200° to 400°C for copper-constantan thermocouples, although not new, have been included for completeness.

1456. RUDNITSKII, A. A. and TYURIN, I. I. **The investigation and choice of alloys for high-temperature thermocouples.** *Zhurn. Neorg. Khim.* **1**: 1074–1090, 1956.

In Russian.

Translation available at Great Britain, Atomic Energy Research Establishment Trans. 798.

Alloys for use in thermocouples at 1350° to 1550°C were investigated. The most stable thermoelectrodes at 1350°C are pure rhodium and the alloy 80% Pt-20% Rn, and at 1550°C the thermoelectric characteristics were less stable. This alloy can also be used at 1800°C for short periods if corundite capillary insulation is used.

1457. RUDNITSKII, A. A. **Absolute thermoelectromotive forces and their application in the study of conversions in copper palladium alloys.** *Izvest. Sektor. Platiny i Drug. Blagor. Metal., Inst. Obschei i Neorg. Khim., Akad. Nauk. SSSR.*, no. **27**: 227–238, 1952.

In Russian. Not examined.

"It had previously been determined that the curve of e vs. composition was linear when the binary alloy was a mechanical mixture of phases, smooth with a maximum or minimum for solid solutions, and broken at a maximum or minimum point when a intermetallic compound was formed. Phase transformations caused sharp changes in e. The integral thermoelectric emf was determined with a thermocouple prepared from the alloy to be studied and a standard metal, Pt or Cu. Another method involved the use of identical standardised couples welded to the ends of a 2- to 3-cm. length of the alloy to be studied, this assembly was placed in a temperature gradient." *Chem. Abs.* **49**: 2143, 1955.

1458. RUDNITSKII, A. A. and POLYAKOVA, R. S. **Alloys of platinum with rhenium.** *Izvest. Sektor Platiny i Drug. Blagor. Metal. Inst. Obshchei i Neorg. Khim. Akad. Nauk. SSSR.* no. **27**: 223, 226, 1952.

In Russian. Not examined.

"Brinell hardness, electrical resistance, thermoelectric emf and microstructure were studied on alloys containing up to 16 wt. % Re.

1459. RUDNITSKII, A. A., POLYAKOVA, R. S. and TYURIN, I. I. **Polymorphic transformation of rhodium.** *Izvest. Sektora Platiny i Drug. Blagor. Metal. Inst., Obschei i Neorg. Khim., Akad. Nauk. SSSR.* no. **29**: 183–189, 1955.

In Russian.

Absolute TE power and Thomson emf in microV/°C. determined for coin purity Rh at various temperatures between 100 and 1200°C. Values at 1030°C. (−1·74, −0·52) represent the upper and lower values for the break in the curve at the transformation temperature.

1460. RUDNITSKII, A. A. **Properties of spectroscopically pure platinum.** *Izvest. Sektor. Platiny i Drug. Blagor. Metal., Inst. Obschei i Neorg. Khim., Akad. Nauk. SSSR.* no. **27**: 195–201, 1952.

In Russian.

"Tests were made on the following 6 Pt specimens: Pt-1, special melt in a ThO_2 crucible; Pt-2, common melt in ThO_2; Pt-3, special melt in a ZrO_2 crucible; Pt-4, common melt in ZrO_2; Pt-5, prepared by method of N.K.

1461. RUDNITSKII, A. A. **Termoelektrisheskiyi sovoystva blagorodnykh metallov i ikh splavov. (Thermoelectrical properties of noble metals and their alloys).** 148 p., *Moskva. Akademii. Nauk. SSSR.* 1956.

In Russian.

AFC Trans. 3724 issued July 1959. (For sale by OTS).

Chief emphasis is placed on the development of a "generally accessible, very simple and rapid" method for the measurement of thermoelectric properties of metals and alloys. The technique uses a "Kurnakov pyrometer" to measure absolute thermal emf of materials. Measured quantities are independent of the shape and dimensions of the specimens.

1462. RUDNITSKII, A. A., POLYAKOVA, R. S. and TYURIN, I. I. **The thermoelectric properties of alloys of palladium and rhodium.** *Akad. Nauk. SSSR. Inst. Obshchei i Neorg. Khim. Izvest. Sektora Platiny i Drug. Blagorod. Metal.* **29**: 190–196, 1955.

In Russian.

For English summary see *Chem. Abs.* **49**: 14527, 1955.

1463. RUSZ, J., MISIOLEK, Z. and BABINSKI, W. **Technology of wire production for thermoelectric elements.** *Prace Inst. Ministerstwa Hutnictwa.* **7**: 292–301, 1955.

In Hungarian with English summary. Not examined.

"A very comprehensive paper, reporting the experiments made of thermoelemnets with wires of (for the upper temperature-limit) Pt, Rh–Pt (1600), Chromel–Alumel (1200), Ni, Cr–Ni (1000), Fe–Constantan (800), Fe–Copel (800), Chromel–Copel (I) (550), Cu–Constantan (400). The temperatures and thermoelectric potentials were measured by aid of the following standard thermoelements: Ir–Ir, Ru; Ir, Rh–Ir, Ru; W–W, Mo; C–Si. The amount of alloying metals and fluxes one must use in order to prepare the alloys for these wires is

described, and how to melt, cast, cold-work, and anneal them." *Chem. Abs.* **50**: 7705, 1956.

1464. SANDERS, V. D. **Review of high temperature immersion thermal sensing devices for in-flight engine control.** *Rev. Sci. Instr.* **29**: 917–928, Nov. 1958.

Typical performance and thermoelectric behaviour of 20 metallic thermocouples that have been calibrated above the melting point of platinum are presented. A review of methods of, and properties of, refractory oxides suitable for thermocouple protection at high temperatures is also given.

1465. SAKURAI, T., KANAYA, K. and SHISHIDO, K. **The thermopile for an infrared spectrometer and its application to a vacuum gauge.** *Tohoku Univ. Res. Inst. Sci. Rpt. Ser. A.* **1**: 313–317, Oct. 1949.

The construction of Bi-Te and Bi-Sb vacuum thermopiles is described and illustrated. They are mounted on mica and the metals are deposited in vacuo by evaporation on thin collodion films. The glass envelopes have rock-salt windows. The resistance of the Bi–Te thermopiles was 1–10 kΩ and of the Bi-Sb 0·1–1 kΩ.

1466. SCHNEIDER, GUNTHER and BOETTCHER, ALFRED. **Iridium thermocouples.** U.S. Patent 2,802,894 (to Deutsche Gold- und Silber-Scheidean stalt vorm. Roessler). Aug. 13, 1957.

Thermocouples of Ir/Re-Ir alloys for high-temperature measurement are described. The emf range for Ir/Re, 90-Ir, 10% is 5–36·13·23 mV at 1500–2100°. The thermocouple is sealed in a gas-tight casing of a glazed thermostable sintered oxide for protection against oxidation.

1467. SEMKO, M. F. and PALATNIK, L. S. **Sensitiveness of thermo-emf "natural thermocouples" to structural changes in high-speed steel.** *Fiz. Met. i. Metalloved.* **7**: 48–52, Jan. 1959.

In Russian.

The dependence of the thermoelectromotive force of natural thermocouples on the type of thermal treatment of P18 steel (0·75%C, 0·3% Mo, 1·55% V, and 18·3% W) and the effects of soaking time at 500 and 600°C on the thermoelectromotive force stability in a standard treated P18 steel were studied.

1468. SHENKER, H., LAURITZEN, J. I., Jr. and CORRUCCINI, R. J. **Reference tables for thermocouples.** *Natl. Bur. Standards Circ.* 508. 71 p., 1951.

The tables give electromotive force (absolute millivolts) against temperature, and temperature against emf in 0·01 mVsteps (except Cu–constantan which is in 1 mV steps); for the following: Pt v. Pt–10% Rh; Pt v. Pt–13% Rh; chromel-alumel; Cu-constantan. And emf against temperature (°F and °C in 10 degree steps) for chromel-constantan.

1469. SHEPARD, R. L., PATTIN, H. S. and WESTBROOK, R. D. **A high-temperature boron graphite-graphite thermocouple.** *Am. Phys. Soc. Bull.* **1**: 119, 1956.

Abstract only of paper given at meeting of the American Physical Society, Pittsburgh, March 15–17, 1956.

A study of the effect of small amounts of boron on the electrical properties of graphite has shown that about one percent of boron changes the thermoelectric power of graphite from $-5\mu v/°C$ for pure graphite to $+15\mu V/°C$ for the boronated graphite with respect to copper at room temperature. A couple comprised of a pure graphite rod and a boronated graphite rod has produced over 100 mv at 3000°C. The thermocouple is sensitive to temperature differences of less than 10°C and stable up to at least 2600°C in neutral or reducing atmospheres such as are found in industrial furnaces or vacuum furnaces. The low electrical resistivity, high thermal conductivity, and excellent machinability of plain and boronated graphite allow convenient instrumentation, fast response, and easy construction of the couples.

1470. SIMS, C. T., GAINES, G. B. and JAFFEE, R. I. **Refractory-metal thermocouples containing rhenium.** *Rev. Sci. Instr.* **30**: 112–115, figs., Feb. 1959.

The thermoelectric force developed by the following junctions up to 2200°C has been measured: Re vs. W, Re vs. Mo, Re vs. W–30Re, and Re vs. Mo–50Re. The thermoelectric force for W vs. W–30Re and Mo vs. Mo–50Re has been calculated. The Re vs. W junction develops about 15 mV at 1000°C and may be usable up to 2600°C. Re vs. Mo develops about 17 mV at 1000°C; the thermoelectric power is low above 1600°C. The outputs of Re vs. W–30Re and Re vs. Mo–50Re couples are low and change signs at about 1200 and 1800°C, respectively. The calculated outputs of W vs. W–30Re and Mo vs. Mo–50Re are high; the W vs. W–30Re output is nearly linear over a wide range in temperature and the thermocouple should be useful to about 2600°C. All of these couples must be used in vacuum or in neutral or reducing atmospheres.

1471. SIMS, C. T. and JAFFEE, R. I. **Further studies of the properties of rhenium metal.** *J. Metals* **8**: 913–917, 1956.

The thermoelectric behaviour of the Pt–Pt–Re thermocouple and the resistance of Re to attack by certain molten metals are discussed. In addition, data are presented on the stress-rupture behaviour of drawn wire, the tensile characteristics of rolled sheet, the variation of Young's modulus with temperature, and the effect of specimen size and fabrication method on the work hardenability. Mechanical properties of thoriated Re are discussed. This includes data on the effect of thoria in Re on tensile properties, ductility, work-hardening, and recrystallization.

1472. SUKHOV, S. A., KADLEC, S. YA. and PAVLYUK, G. D. **Electrolytic thermocouples.** *Izmeritel. Tekh.* p. 35–37, Feb. 1959.

In Russian.

Electrolytically produced thermocouples (*e.g.*, constantan coated with copper) are compared with ordinary bimetal couples with regard to emf-temperature relationships and fields of application.

1473. **Thermoelectric couple.** *Elec. World* **31**: 308, 1898.

A sensitive thermocouple is described. One element is an alloy of copper and 40% nickel; the other is iron. Resistance is not affected by temperature. Strongest yet discovered next Bi–Sb combination. Patented in Germany.

1474. TIKHONOV, V. I. **Measurement of electrical fluctuations with the aid of thermoelectric devices.** *Zhurn. Tekh. Fiz.* **25**: 817–822, May 1955.

In Russian.

It is suggested that thermocouples and thermistors may be used as standard noise sources for measurement of noise spectra. The theory of the method is discussed and a formula is derived determining the accuracy of the measurements. A brief report is also given on an experiment.

1475. TRIGGER, K. J., CAMPBELL, R. K. and CHAO, B. T. **A tool/work thermocouple compensating circuit.** *Am. Soc. Mech. Engrs. Trans.* **80**: 302–306, 1958.

It is shown that serious parasitic emf are introduced if a dissimilar metal is used to connect a carbide insert to the emf measuring instrument in a tool/work thermocouple, but that the effect can be minimized by the use of a suitably designed compensating circuit. The conditions necessary to achieve complete compensation are explained and results given to indicate the reliability of the method.

1476. UBBELOHDE, A. R., BLACKMAN, L. C. F. and DUNDAS, P. H. **A graphite-graphite thermocouple for high temperature.** *Chem. & Indus.* **19**: 595–596, May 9, 1959.

The possibility of, and difficulties in, using the thermoelectric power developed between specimens of graphite of different crystal orientations, when formed into a circuit with junctions at different temperatures, are discussed. Details are given of the construction of thermoelectric power units that remain stable at high temperatures. The thermojunction at the hot end is formed between pyrolytic graphite highly oriented with respect to the α axis and a specimen of heat-treated polycrystalline graphite.

1477. U.S. Atomic Energy Commission, Oak Ridge National Laboratory, Oak Ridge, Tenn. **Thermocouple research,** by D. L. MCELROY. 87 p., Oct. 1957. (Rept. 2467). (Prog. Rept. 1). (AD–153–231).

Description of experimental equipment constructed and operated for: (a) thermocouple calibration; (b) time-at-temperature studies of in thermal-emf ; (c) heat treating of wires. A brief literature survey based on nearly 4000 references has been included to summarize the large amount of information existing on thermocouple technology.

1478. WAGNER, RICHARD. **Komplexhomerseklet. (Composite temperature.)** *Idojaras* **58**: 72–77, Mar./Apr. 1954.

In Russian.

"The author developed an electrical instrument measuring air temperature, radiational heat gain, and heat loss by evaporation and wind. The value indicated by the instrument is termed composite temperature. Composite temperature values can be reduced to 2°C if desired. The instrument was successfully used in bioclimatological and micrometeorological research." *Meteorol. Abs. Bib.* **6**: 750, 1955.

1479. WECHSUNG, H. **Present technique of thermocouples.** *Arch. Tech. Messen*, **216**: 19–20, Jan. 1954.

In German.

A review of the current range and frequency limits of thermocouples. Types considered are: open (air) types; vacuum types with all connections through pinch, with heater and couple connections at opposite ends of bulb, with straight-through heater. Curves are given for three types, based on 1·5% error, which show the relation between current range and highest usable frequency; the ordinates extend from 1 mA to 6A, and up to 1000 Mc/s.

1480. Westinghouse Electric Corp., Pittsburgh, Pa. **Insulation resistance of thermoelectric magnesia insulated chromel-alumel thermocouples,** by F. GAIDOS and H. L. GLICK. 13 p., 1954(?). (Rept. WAPD–S5W–EP–23).

The thermocouple consists of a stainless steel jacket, nominally 1/16 in. OD. housing size 30B and S gauge chromel and alumel wires insulated with magnesium oxide. The functional properties of the thermocouple in high temperature and high neutron density environments were measured.

1481. WICK. **Thermoelectromotive force with silicon.** *Phys. Rev.* **25**: 382, 1907.

A thermocouple of silicon and copper is made by copper plating silicon. The thermoelectric power is −395 microvolts per degree centigrade.

CHEMICAL COMPOSITION INDEX

Ag—251, 258, 270, 299, 324, 345, 420, 563, 619, 675, 808, 813, 833, 943, 1059.
Ag–Al—520.
Ag–Au—166.
AgBr—44, 45, 385, 386, 589, 747, 914.
AgCl—45, 387, 747, 1026.
$AgBiSe_2$—624.
Ag–Cu—534, 535, 536, 537, 595.
$AgGaS_2$—34.
$(Ag–Ga)Se_2$—34.
$(Ag–Ga)Te_2$—34.
AgFe (Te_2, Se_2, S_2)—1114.
Ag–Mn—271, 911.
Ag_2P—764.
Ag–Pd—593, 911, 994, 1032.
Ag–Pt—903, 911.
Ag–Pt–Au—904.
Ag_2S—1025.
Ag–Sb—760.
$AgSbSe_2$—624.
$AgSbTe_2$—624, 1074.
Ag_2Se—843, 1064.
Ag_2Te—844, 845, 1064, 1109.
Al—22, 163, 181, 195, 211, 234, 258, 299, 932, 933, 934, 938, 952, 982, 983, 985, 990, 992.
Al–alloys—22, 154, 376, 601, 708.
Al–Ag—518, 519, 521, 936.
Al–As—8.
(Al–Ga)As—530, 531.
Al–Bi—520.
(Al–Mg)Tio_3—1080, 1081.
Al_2O_3—582, 583, 919, 918, 920.
Al–Sb—748, 839, 882, 939, 974, 1088.
Al_2Te_3—839.
As_2Te_3—713.
Au—251, 258, 270, 299, 324, 420, 563, 619, 732, 808, 813, 833, 1059.
Au–Mn—271.
Au_2P_3—764.
Au–Pd—911.
Au–Pt—216.
BaO—742, 749.
$BaO–V_2O_5–P_2O_5(Na_2O)$—533.
BaS—699.
BaSe—266.
(Ba–Si)O—1108.
(Ba–Sr)O—678, 899.
BaTe—890, 891.
$BaTiO_3$—1037.
Be—791.
BeO—749, 920.
Bi—11, 172, 296, 303, 304, 412, 413, 414, 581, 617, 736, 737, 740, 754, 755, 767, 793, 835, 847, 952, 977, 980, 987, 988, 991, 1021, 1086.
Bi–Cd—836.
Bi–Pb—835.
Bi–Sb—794.
(Bi–Sb)(Bi–Sn)—145.
Bi–Sn—586, 989.
Bi (Ti, In, Mg, Tl, Mg)—793.
Bi (Tl, In, Mg)—757.
Bi_2O_3—822.
Bi–Te—497, 929.
Bi_2Te_3—7, 38, 83, 84, 85, 86, 87, 354, 366, 501, 527 569, 677, 687, 688, 690, 692, 695, 696, 709, 711, 712, 713, 767, 781, 820, 838, 864, 908, 981, 1000, 1004, 1027, 1061, 1063, 1066, 1090, 1093, 1094, 1096, 1097.
$Bi_2(Te_3–S_3)$—676.
$Bi_2(Te_3–Se_3)$—7, 134, 532, 639, 660, 694, 714, 881, 1010.
$(Bi_2Sb_2)Te_3$—134, 502, 520, 539, 1014.
Bi_2S_3—665, 727, 765.
Bi–Se—603, 998, 999.
Bi_2Se_3—505, 716, 766, 767, 850, 998, 1000.
Bi_3Se_4—998.
$(Bi_2–Sb_2)(Te_3–Se_3)$—544.
B—751, 1003, 1052.
BP—1024.
Brasses—976.
C—548, 746, 747, 800, 801, 802, 803, 865, 901, 902, 1041, 1045, 1046, 1053.
C—diamond—689.
CaO—678, 749.
Cd—172.
CdO—509, 542, 600, 729, 749, 1098, 1099, 1101.
CdS—742, 777.
Cd–Sb—726, 753, 772, 829, 922, 923, 924, 925, 1050, 1111.
Cd–Sn—584.
CdTe—609, 742.
Cd–Zn—795.
(Cd–Zn)Sb—823.
CeB_6—970, 971.
CeO—605.
CeS—674, 1080, 1081.
CeSe—1080, 1081.
Cu—22, 173, 174, 181, 243, 251, 252, 255, 258, 267, 268, 270, 283, 299, 324, 341, 342, 420, 576, 618, 661, 778, 807, 813, 815, 817, 906, 932, 937, 952, 958, 1059.
Cu alloys—183, 363, 376.
Cu–As—956.
Cu–Au—165, 166, 975, 994.
CuCd—779, 955.
Cu(Cr,Mn)—739.
Cu(Fe)—562.
$CuFeS_2$—558, 616, 1115.
CuGe—779.
$CuGaS_2$—34.
$CuGaSe_2$—34.
$CuGaTe_2$—34.
CuIn—779.
Cu–Mn—499, 911, 1029.
CuNi—994, 1005.
Cu o—727, 858, 917, 918, 921, 1117.
Cu_2o—70, 210, 485, 506, 519, 572, 702, 730, 848, 993, 1117.
CuP—956.
Cu_2P—764.

Cu_3P—764.
CuPd—911.
Cu–Pt—911, 965.
CuS—1025.
Cu(S–Se)—498.
Cu–Sb—779.
Cu–Si—360.
$CuSo_2$—919.
$CuSbTe_2$—624.
Cu–Sn—508, 779.
Cu–Zn—779.
Co—952, 984, 985.
CoO—600.
$CoSb_3$—620, 621, 622, 623.
Cr—1015, 1047.
CrO—542.
Cr_2O_3—582, 583, 645.
CrS—1069.
$CrSb_2$—492.
Cr–Si—705, 706, 892, 893, 894, 1042.
Cr(Te–Se)—1043.
Cs—489, 809, 810, 811, 812, 816, 818.
Cs_3Sb—967, 968.
Cs_2Sb—969.
Fe—22, 181, 193, 194, 258, 693, 932, 933, 934, 952, 1084.
Fe alloys—154, 658, 739, 1005.
Fe–C—540.
Fe–Cu—916.
Fe–Co—1107.
Fe–Constantan—507.
Fe(Cr, Mn)—281, 739.
FeO—542, 674.
Fe_2O_3—854, 855.
Fe_3O_4—785.
Fe_3Pt—511.
FeS_2—643, 710, 718, 863, 906, 1025, 1069.
Fe–Si—360, 686, 797, 798, 799.
$FeSi_2$—496.
Ga—604.
GaAs—525, 626, 632, 679, 940.
GaAs—Ga_2Se_3—883.
GaSb—747, 748, 939.
Gd—953.
Ge—116, 238, 275, 314, 330, 333, 335, 336, 337, 338, 371, 377, 393, 424, 447, 462, 467, 490, 524, 571, 615, 634, 635, 637, 650, 652, 666, 667, 668, 682, 724, 746, 747, 769, 780, 804, 834, 869, 873, 942, 973, 1106, 1007, 1019, 1020, 1031, 1051.
Ge alloys—784.
Ge(Ga, Sb)—680, 681, 683.
Ge(Sb, Bi)—748.
GeS—750, 1102.
Ge–Si—1022.
Ge–Te—853, 940, 1082.
Glasses—704, 743, 909.
Hg—317, 662.
HgO—749.
HgSe—551, 630, 631.
HgTe—87, 579, 630, 631, 659, 782.
Hg (Te–Se), (Te–SeS)—895, 896.
Hf—953.
Hf–(B,C,N)—971.
Hf–(Se, Te)—831.
In—305, 926.
In alloys—225.
InAs—514, 567, 585, 940, 1070, 1071.
InAsP—566, 568.
In_6Ga_4—948.
InGaAs—491, 949.
InP—679.
In–Pb—1039, 1040.
InSb—301, 449, 500, 514, 526, 567, 585, 628, 651, 670, 682, 747, 864, 939, 944, 959, 961, 964, 1028, 1070, 1071.
In_2Se_3—846.
In–Sn—972.
In–Te—638, 1100.
In–Tl—1040.
Ir—783, 907, 1084.
K—489, 809, 810, 811, 812, 813, 815, 816, 818.
LaB_6—971.
$LaBaTiO_3$—1081.
$(La–Sr)Mno_3$—1067, 1068.
Li—489, 809, 810, 811, 812, 816, 818, 1001.
Li(Co–N)O—132, 1080, 1081.
Li(Mg–Ni)O—1080, 1081.
(Li–Mn)O—719, 1078.
Mg–alloys—222, 223, 224, 263.
Mg–Bi—793, 870, 871.
Mg_2Ge—503, 1091.
MgO—742, 749, 819, 900, 1104.
MgO–CoO—674.
MgO–FeO—674.
MgO–NiO—674.
$MgO–ZrO_2$—867.
Mg_2Pb—957, 1091.
Mg_3Sb_2—561, 573, 574.
Mg_2Si—503.
Mg_2Sn—301, 770, 957, 1091.
Mn–Cu—499.
Mn–Ni—510, 979.
MnO—932.
$MnO–TiO_2$—859.
Mn–Si—797, 798, 799.
$MnSi_2$—892, 893, 894.
Mo—258, 629.
Mo_2C, MoN, Mo_2N, Mo_2B_5—970, 971.
Mo–Cr—636.
Mo–Hg—874.
MoS_2—70, 727, 821.
$MoSi_2$—523, 1042.
Na—489, 809, 810, 811, 812, 813, 815, 816, 817, 818, 1001, 1083.
Na–Au—1016.
NaCl—191, 386.
$(Na–K)NH_3$—612, 789.
$Na_2O–Tio_2$—859.
NbB_2, NbC, NbN—971.
NdB_6—970.
Ni—22, 181, 258, 675, 841, 842, 952, 1084.
Ni–Cu—593.
Ni–Cr—261, 646, 771, 994, 997.
Ni(Cr, Mn)—739.

Ni_2FeO_4—856.
(NiO–FeO)(Fe_2O_3)—785.
Ni–Mn—510, 979.
Ni–Hg—756.
Ni–Mo—935.
NiO—210, 572, 729, 912, 913, 932, 1095.
Ni–Pd—512, 513.
NiS—717.
Ni–Si—360.
Ni–Te—1113.
NiZn–Fe_3O_4—1057, 1060.
Np—701, 787.
Pb—273, 305, 345, 412, 413, 423, 444, 564, 588, 758, 835, 926.
(Pb–Bi)–Te—889.
Pb–Cd—1112.
PbO—542.
PbO_2—900, 918, 919.
PbS—70, 262, 515, 547, 613, 614, 641, 648, 742, 746, 804, 837, 900, 946, 947, 1013, 1025, 1035.
Pb(S–Te)—750.
Pb–Sb—768, 1023, 1110.
Pb–Se—560, 613, 742, 805, 806, 880, 946, 947, 1009.
Pb (Se–Te)—748.
PbTe—328, 554, 560, 570, 610, 725, 742, 775, 788, 805, 806, 864, 880, 887, 946, 947, 1009, 1082, 1097.
Pd—227, 258, 732, 1084.
Pd(Ag, Rh)—1032.
Pd–Ni—512, 513.
Pd–U—580.
PrB_6—970.
PrO—824.
Pt—258, 562, 576, 597, 629, 661, 732, 833, 907, 1058.
Pt–(Ag, Au)—903, 904.
Pt–Au—911.
Pt–Hg—874.
Pt–Mo—897, 898.
Pt–(Na, Ba)—1016.
Pt–Rh—783.
Pt–Th—552.
Pt–U—591.
Pu—700, 786.
Re–Ir—707.
Rb—489, 809, 810, 811, 812, 816, 818, 868.
Rd—1084.
Rh—663, 783, 907.
Ru—966.
S–Se—498.
Sb—519, 736, 740, 745, 950, 952, 1086.
Sb–Ag—520, 760.
Sb–Al—520.
Sb–Ag–Al—520.
Sb_2Se_3—602, 665, 876.
Sb–Te—647, 728, 1062.
Sb_2Te_3—713.
Sb–Zn—555, 611, 773, 774, 792, 829, 888, 925, 941, 1033, 1034, 1103.
Sb–Zn–Bi—520.
Sb–Zn–C—520.
Se—720, 721, 722, 723, 727, 744, 745, 776, 930, 962, 996, 1002, 1065.
Se gray—578.
Se–Au—1008.
Se(Br)—528.
Se(Br,Cl,I)—671, 672.
Se–S—498.
Se–Te—549, 550.
Si—116, 371, 666, 669, 746, 747, 804, 986, 991.
SiC—517, 553, 572, 576, 666.
Si–Ge—750, 1022.
Si (Fe–Cr–Mn)—797, 798, 799.
Si–Sn—750.
SiO_2—900.
SmN—1049.
Sn (gray)—345, 575, 684, 685, 861, 862.
Sn (White)—172, 296, 305, 542, 564, 587, 860, 926, 943.
(Sn–Ag)Bi—1033.
Sn–Cd—1112.
(Sn–Ge)Te—495.
SnO—542, 752.
(Sn–Pb) Te—266, 493, 494.
Sn–Sb—1056.
SnSe—522.
SnTe—266, 715.
SrO—749.
TaB_2, TaC, TaN—971.
Ta–Hg—874.
Ta–Te—1048.
Te—11, 504, 519, 633, 642, 736, 746, 849, 952, 995, 1030, 1038.
Te alloys—1036.
Te–Al—520.
Te–(Au–Sb)—559.
Te(Sb)—654, 655, 656, 657, 728, 1062.
Te–Se—549, 550.
Te–Ta—1048.
Th—305, 832.
ThO—517, 920, 1070.
Th–Pt—552.
Th (Se, Te)—831.
Ti—258, 703, 927, 978, 1092.
TiB_2—970.
Ti(Se, Te)—831.
TiC—970.
TiN—971.
TiO_2—391, 516, 557, 653, 698, 866, 884.
Ti_2O_3–Ti_3O_4—915.
TiO_2–Na_2O—859.
Tl(Cl, Br)—747.
Tl_2S—727.
U—598, 606.
U Cmpds.—1082.
UO_2–U_3O_7—529.
V alloys—905.
VC, VB_2, VN—970, 971.
V_2O_5—590, 727.
W—258, 629.
WC, W_2B_5, W_2N—971.

W–Hg—875.
W–O—542.
WO_3—727, 1012.
W(Ta, Mo)—852.
Yt—759.
(Y–Ca)TiO_3—1080, 1081.
Zn—160, 161, 172, 796.
(Zn–Cd)Hg—763.
ZnF_2—599.
ZnO—210, 485, 730, 741, 749.
ZnSb—611, 773, 774, 792, 829, 888, 925, 941, 1033, 1034, 1103.
Zn_3P_2—764.
ZnSb–Pbs—648.
ZnTe—556, 734.
Zr(Se, Te)—831.
ZrC, ZnB_2—970.
ZrN—971.
ZrO—517.
ZrO_2–MgO—867.